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COST EFFECTIVENESS OF
TWO VS. THREE LEVELS OF MAINTENANCE
FOR
TURBINE ENGINES
IN THE AIR FORCE INVENTORY

THESIS

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AFIT/GLM/RQ/90S-49

The opinions and conclusions in this paper are those of the author and are not intended to represent the official position of the DOD, USAF, or any other government agency.

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THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

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Master of Science in Logistics Management

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Preface

The purpose of this study was to examine the life cycle costs (LCC) for Air Force turbine engines, and compare the costs of maintaining engines in two, three, and modified three level maintenance concepts. With the Air Force moving toward two level maintenance it is important to understand the cost implications of this move.

An accounting model, the "Super Operating and Support Cost Model," used by the Propulsion SPO, ASD/YZ, at Wright Patterson AFB, to estimate LCC for engines, was run to provide much of the data in this study. The results point out that certain factors can drive the LCC for a two level maintenance concept to exceed the costs for three level maintenance. Further studies should be done to try to determine under what conditions this could take place.

Throughout my efforts I received help and guidance from many people. I greatly appreciate the time, assistance, and expertise shared by my faculty advisor, Dr. Ben L. Williams, and the aid Lt Col Robert D. Materna gave in helping me define the focus and direction of this research. I would also like to thank the people at the Propulsion SPO for their cooperation in providing greatly needed information. Most of all, I would like to thank my wife, Liz, for her patience and understanding. Her caring made a seemingly endless effort much more bearable.

John T. Schiefen Jr.

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Abstract

This study examined the life cycle costs (LCC) for Air Force turbine engines. Specifically, the research compared the costs for two, three, and modified three level maintenance concepts. To achieve the research objectives, a LCC model, the "Super Operating and Support Cost Model (SOSCM)," was used. SOSCM is used by the Propulsion SPO, ASD/YZ, at Wright Patterson AFB to estimate costs for Air Force engines. A sensitivity analysis was run on a generic test case to determine the effect of changes in certain cost drivers on LCC. There were a few important findings. First, for this case, the LCC for the two level concept was 14.7% greater than the costs for three levels of maintenance. Two factors accounted for most of the difference. The number of spare engines required increased, and second destination transportation costs rose sharply. The study also showed that changes in some factors have a greater impact on the costs for two levels of maintenance than three. Overall, the research points out that it should not be assumed that moving to two levels of maintenance will lower costs. Engine types should be considered individually to determine the most cost effective maintenance concept.

COST EFFECTIVENESS OF TWO VS THREE LEVELS OF MAINTENANCE FOR TURBINE ENGINES IN THE AIR FORCE INVENTORY

I. Introduction

General Background

The Air Force, in an effo t to reduce support costs, is moving to two levels of maintenance (6:1). The concept was originally conceived for avionics subsystems, and tested in the B-52H and KC-135A systems (6:1). Recently the concept has been cleared for implementation Air Force wide, with future growth expected to include moving the intermediate level engine maintenance to the depots (18:1). Is a two level maintenance concept the most cost effective, though, for turbine engines in the Air Force inventory? Currently three concepts are being used. The first is a two level concept. Next, is three levels of maintenance, with an intermediate shop at each operating location. The last concept is a modified three level concept, with the intermediate level tasks being accomplished at regional maintenance centers (19:1). The Propulsion SPO (ASD/YZ) at Wright Patterson AFB uses a model which they developed to estimate the operating and support costs for engines in the full-scale development and production phases

of the acquisition process. This model is called the "Super Operating and Support Cost Model" (SOSCM) (1:1). Equations in the model follow Logistics Support Cost model equations tailored for Air Force engines (1:1). SOSCM can be further tailored to represent specific engines. The inputs and assumptions are validated periodically using actual maintenance data obtained from AFLC and the using commands, or projected data estimated by an "Engine Review Organization" in accordance with AFM 400-1 (13:17-18).

Results from the model indicate that two levels of maintenance is not always the lowest cost alternative. For example, the most cost effective maintenance concept for the B1-B engine, according to the model, is the three level concept (25:1). This conflicts with the Air Force goal to save money by moving to two levels of maintenance. It is important to determine if the model is accurate, and to understand the factors which drive concepts other than the two level concept, to be more cost effective for some engines.

Life Cycle Cost (LCC). Life cycle cost is "the total cost of an item or system over its full life (11:8)." LCC includes the "acquisition costs (research, development, test and evaluation; production cost, including the initial investment for product support capability); and recurring operating and support cost or 'ownership cost' (operations, maintenance, and support) (10:sec 22,1)." The increasing

complexity of Air Force weapon systems makes the estimation of LCC an extremely difficult task. To accomplish this, mathematical models are often developed. These models can be used to provide a baseline, estimate cost consequences of a particular action, or identify the cost consequences of various choices (10:sec 22,2). There are three types of models used to estimate LCC. The first simply relates a cost category and a single variable. Next in complexity is a model which uses regression techniques to relate any number of variables to the overall cost. An equation is "fit" to the data, and used to make cost estimates and predictions. These equations are often referred to as "Cost Estimating Relationships" (CER). In the case of turbine engines, CER models can use a variety of variables. Some variables may represent costs, and others may be characteristics of the engine, such as the specific fuel consumption, weight, or turbine inlet temperature. An advantage of this type of model is the limited amount of data needed (28:25-26). The most complex model is an "accounting" model. This type of model uses engineering estimates of component reliability and maintainability (r&m) and cost characteristics to estimate the total costs (10:sec 22,2). Accounting models require large amounts of data compared to the other models discussed, and the accuracy of a CER can be nearly the same (28:vii).

for each year of interest in the life cycle. The result is a matrix which contains a complete list of all items which require maintenance actions (1:8). For example, the matrix includes information on engine, LRU, and SRU removal rates, base and depot maintenance man-hours per event, and unit prices (among other information) (1:8-10).

```
   1st Indenture        2nd Indenture
/--------------------------------------\
|                   |  SRU's / Modules |
|                   |    Fan           |
|                   |    Compressor    |
|       Whole       |    Augmentor     |
|       Engine      |    Gearbox       |
|                   |    Etc.          |
|                   |  LRU's           |
|                   |    Fuel Pump     |
|                   |    Fuel Control  |
|                   |    Etc.          |
\--------------------------------------/
```

Figure 1. Engine Breakdown Structure (1:5)

SOSCM outputs costs in a variety of ways. First, the total annual flying hours and costs are estimated. These are used to calculate the annual cost per engine flying hour (broken down by year). The data is also divided into cost categories for spares, base and depot material, and base and depot labor dollars per engine flying hour per year (1:10). The model also estimates support equipment, fuel, and transportation costs (1:13).

Table 1. Standard Factors (1:4)

<u>Program Definition Factors</u>

Number of Production Years
Number of Steady State Years
Total PAA Engines

<u>Operational Concept Factors</u>

Number of Bases
Number of JEIMS
Utilization Rate (Hrs/Mo)
Percent of Fleet in CONUS
Fuel Utilization (Gal/EFH)

<u>Logistics Support Factors</u>

Base Repair Cycle Time (Days)
Depot Repair Cycle Time CONUS (Days)
Depot Repair Cycle Time Overseas (Days)
Order and Ship Time CONUS (Days)
Order and Ship Time Overseas (Days)
Automatic Resupply Time CONUS (Days) *
Automatic Resupply Time Overseas (Days) *
Spares Confidence Factor

(The factors above require an engine, LRU, and SRU input value.)

Item Weight/Packaged Weight Ratio
Recurring Support Equip. Cost Factor (% unit cost)
Pipeline Spares Factor

<u>Standard Cost Factors</u>

Fiscal Year Dollars
Base Labor Rate ($/Hr)
Base Material Rate ($/Hr)
Depot Labor Rate ($/Hr)
Depot Material Rate ($/Hr)
Fuel Cost ($/Gallon)
Packaging Rate ($/Lb)
CONUS Shipping Rate ($/Lb)
Overseas Shipping Rate ($/Lb)
Part Number Introduction Cost *
Annual Base Support Management Cost *
Tech Data Acquisition Cost ($/pg) *
Tech Data Update Cost ($/pg) *
Tech Data Repro Cost ($/pg) *

<u>Supplementary Factors</u>

Whole Engine Spares (Quantity)
Support Equipment (M$)
Common
Peculiar

* Not currently used in the model

Specific Problem

Determining the Life Cycle Cost for the various maintenance alternatives is one of the major tasks which must be completed before choosing a maintenance concept. The complexity of a turbine engine makes this very difficult. With the Air Force moving to two levels of maintenance, it is important to understand whether this concept is the most cost effective for all engines. This understanding must begin by insuring that the model used to compute LCC for these engines is realistic and accurate. If the model is not accurate, changes must be incorporated. If the model, and its assumptions, are accurate, it is important to understand the factors which drive costs for maintenance concepts, other than the two level concept to be more cost effective. This would allow the Air Force to make decisions on whether to move to two levels of maintenance for turbine engines with increased confidence and understanding of the cost implications. To summarize, the Air Force, in an effort to reduce costs, is moving to two levels of maintenance for turbine engines. The cost implications of this move is not fully understood. This study will provide some of the information needed to understand the changes in cost that will accompany the switch from three to two levels of maintenance.

Research Questions

To determine the validity of the cost model for the purposes of this study the following questions will be considered:

1) What are the assumptions that are made within the model?

2) Are the assumptions accurate?

3) What does the model include, and does it allow the user to input all of the information needed to estimate the LCC for a turbine engine?

4) Are all of the inputs and assumptions reviewed and updated by the "Engine Review Organizations" in their attempt to validate the model, and are the findings of the organizations fed back into the model?

In an effort to analyze the cost implications of the different maintenance concepts, these three questions will be considered:

1) What are the factors within the model that drive maintenance costs for the three maintenance concepts?

2) Which of these factors can drive the costs for a two level concept to exceed those for the other maintenance concepts (making the other concepts more cost effective)?

3) How sensitive is the LCC to those factors?

Scope and Limitations

Repair Level Analysis (RLA) is used to evaluate a maintenance action to find out if it is more cost effective to do the task or discard the item. RLA is also done to determine where the task can be accomplished most cost effectively (17:217; 12:2). Estimating life cycle cost is a major consideration in the determination of the best maintenance concept for an item or system. Other things are considered though, like the availability of manpower or spare parts (17:219; 4:104-109). This research effort will focus entirely on the process of estimating LCC. The other factors considered in the RLA process will not be examined. Specifically, the study will look at the Super Operating and Support Cost Model (SOSCM) used by the Propulsion SPO (ASD/YZ) to estimate LCC for turbine engines in the USAF inventory. The validity of the model, and its assumptions, for the purposes of this study, will be considered. Due to time limitations this study will not attempt to verify or calibrate the model. These processes would require a full analysis of the computer code to insure that it is operating properly. This step is normally done while developing the model. The research will also determine the factors which drive LCC for the three maintenance concepts, with the goal of determining which factors drive concepts, other than two levels of maintenance, to be the most cost effective. The

cost model itself will not be altered. Following the analysis comments on the applicability of the model will be furnished along with any possible recommendations.

Thesis Organization

This research involves the review and operation of a cost model (SOSCM). The model will be used to provide an understanding of the cost drivers for each of the three maintenance concepts for turbine engines. To accomplish this, the thesis is organized as follows:

I. Introduction
II. Review of the Literature
III. Methodology
IV. Analysis and Modeling
V. Conclusions and Recommendations
Appendices
Bibliography

II. Review of the Literature

History of Two Level Maintenance

The recommendation to move to two level maintenance actually began in the early 1970's. At that time The Rand Corporation did a study which compared the current weapon system support structure to what they called the "Relocation Activities Alternative (RAA)." The main objective of RAA was to reduce recurring costs of operation (8:113). This concept was furthered by the "Defense Resource Management Study (DRMS)" promoted by Secretary of Defense Donald Rice. The final DRMS report was published in February 1979, and dubbed the "Rice Report." This report limited its findings to four functions. One of these was entitled "Logistics Support." This section included case studies in which RAA was applied to the avionics subsystems for the B-52G/H and the KC-135A systems (9:vii). Results from these cases showed potential savings of 18000 personnel. These savings, coupled with savings achieved through economies of scale in spare parts orders and other areas, equated to an estimated $250 million per year. Over 60% of these savings came from changes in the base support structure (8:113). This was achieved while maintaining the systems at a higher operational readiness rate than the current support structure (8:113).

The executive summary in the Rice Report outlined some important findings and recommendations. One of the findings was that "over one third of the defense budget was consumed, and a similar fraction of manpower employed, in the delivery of logistics support (9:xii,43)." This fact highlights the importance of logisti s support in the DOD. One of the four design principles reccmmended in the report was to "consolidate off-equipment maintenance at a level that permits capture of economies of scale, and reduces the vulnerability of some support resources (9:xiii)."

Two level maintenance was cleared for implementation Air Force wide late in 1989 (15:1; 18:1). The goal is to implement the concept for avionics subsystems, and to move to engines in the future. In each case the intermediate repair capabilities will be moved to the depot (16:1; 18:1). Currently, organizations have begun documenting the process used to estimate spares requirements, so that if the Air Force does move the intermediate repair tasks to the depot line, new estimates can be made (5:1).

Engine Maintenance

Determining a maintenance concept for an engine is more complex than deciding the number of maintenance levels. Each engine model is unique, and a maintenance concept must be tailored to fit the individual characteristics. For example, both the F100, found in F-15s and F-16s, and the

F110, used in some F-16s, are fighter engines. Each uses three levels of maintenance. Due to design differences, though, the division of tasks at each level varies (22:1). The F108, the engine on the KC-135R, uses a modified three level concept. A modified three level concept has also been chosen for the F117, the C-17 engine. Like the F100 and F110, the differences in the division of tasks make the two maintenance concepts unique (20:1). When determining the cost effectiveness of a maintenance concept these differences must be considered.

Three Level Maintenance. The F100 engine, produced by Pratt and Whitney, is a modular design (22:1). This means that sections of the engine can be removed and repaired or replaced as units. Examples include the fan, compressor, turbine, augmentor, or gearbox modules (22:1). Design and reliability and maintainability characteristics of this engine model drove the decision to use three levels of maintenance (22:1). Repairs at the organizational level, which occur on the aircraft, are limited to the removal and replacement of whole engines, controls, and accessories (22:1). The intermediate shops at each operating base take the engines and break them into modules. Some minor module repairs can be done, but most of the work on the modules, controls, and accessories is sent to the depot at San Antonio Air Logistics Center

(SA-ALC) (22:1). There modules are placed in special test stands, disassembled, repaired, and reassembled (22:1).

The F110 engine, produced by General Electric, also uses three levels of maintenance, but since it is a much different design it requires a different division of tasks. This engine model is not designed in modules like the F100. Components are removed and replaced separately (22:1). Tasks at the organizational level are still limited to removal and replacement of whole engines, controls, and accessories (22:1). At the intermediate level shops components are removed and often repaired, unlike the F100 which limits much of the intermediate level work to removal and replacement of modules. The depot for the F110, located at Oklahoma City Air Logistics Center (OC-ALC), handles any work too complex for the I-level shops (22:1).

In these cases three levels of maintenance is used. O-level work is similar. The modular design of the F100, though, requires an extra level of disassembly too complex for I-level shops. This added level is unnecessary for the F110. This makes it possible for the F110 engine to be broken into components at the I-level, and often repair them there. In the case of the F100 this level of repair is located at the depot. Here the design of the two engine models has determined the division of tasks for their unique maintenance concepts.

Modified Three Level Maintenance. Similar differences are found when examining engines with a modified three level maintenance concept. One of these engines is the KC-135R engine, the F108. This engine shares a common core, and many external accessories, with the F110 and F101 (the B-1 engine) (20:1). This means that many parts have extensive testing and experience behind them. Because of this the F108 is very reliable, and requires less maintenance (20:1). As a result there is no need for an intermediate shop at each operating location. In fact, there is only one "Regional Maintenance Organization (RMO)," at McConnell AFB, Kansas (20:1). O-level tasks consist of the removal and replacement of whole engines or "Line Replaceable Units (LRU's)." For this engine LRU's up to two deep (i.e. one other LRU must be removed to get to another) is considered O-level work (20:1). External components, like controls and accessories, are sent to the depot at OC-ALC (20:1). At the I-Level shops other exterior components "Shop Replaceable Units (SRU's)" are removed and sent to the depot. Internal components, also called SRU's, are also removed at I-level shops. Many of these, though, are repaired at the RMO, with any extremely complex work sent on to the depot (20:1).

The C-17 engine, the F117, is not a derivative engine like the F108, and is not expected to be as reliable. Because of this, two RMO's are being set up instead of one. One will be located in Charleston, SC. The location of

the other, on the west coast, has not been released (20:1). The C-17 engine is also a modular design, unlike the F108. This, as in the case of the F100 and the F110, results in differences in the division of tasks. Like the other engines discussed, work at the organizational level is limited to the removal and replacement of whole engines, controls, and accessories (20:1). At the RMO's, modules are removed and broken into components. Troubleshooting is done to determine the defective part(s), and some minor repairs are completed. The majority of the work, though, is sent to the depot at OC-ALC (20:1). Although both the F108 and the F117 engines will use a modified three level maintenance concept, there are differences in the number of of RMO's and in the division of tasks at each maintenance level. These differences can be attributed to the unique design and r&m characteristics of each engine model.

Engine Factors

The complexity of turbine engines requires careful tracking and estimation of certain "factors." Among other things, these factors can be used to estimate support costs and determine the most cost effective maintenance concept for an engine model. Air Force Manual 400-1 defines these factors as "quantitative values of operational performance or logistics support expressed in terms that can be used in

various management, requirement, and assessment systems and models (13:41)." The factors represent fleet averages of various characteristics, and are required to be estimated for times of peace, war surge, and sustained wartime usage (13:41). The manual divides these factors into two types, primary and secondary. Primary factors include removal rates, pipeline times, and Jet Engine Intermediate Maintenance (JEIM) return rates. Examples of secondary factors include operating time per engine flying hour, cycle to flying hour ratio, inspection intervals, and maximum operating limits (13:41). Primary and secondary factors are tracked for two categories of factors. The first is "Actual Engine Factors." These reflect recent historical data on the engine model. The next category is the "Mature Engine Factors." These represent values at some future time, when development has stabilized (13:41). These factors make it possible for models like SOSCM to provide estimates of operating costs and support requirements.

<u>Actual Engine Factors</u>. The "Actual Engine Factors," based on recent historical data, are generally collected from users for the preceding year. The AFLC Engine Program Manager is responsible for managing and updating the factors. This manager also keeps track of any changes to the factors, and conducts mid-year reviews (13:46). The resulting data is recorded , and a master file kept, until the engine model is retired (13:44). The data is useful for

a number of purposes. The data can be used to estimate the number of spares needed. It can also be used to determine trends for forecasting of future requirements (13:46). Managers can also use the data for day-to-day management as benchmarks for performance (13:41).

Mature Engine Factors. "Mature Engine Factors," as stated earlier, represent values at a future point in time. These values are estimates, and must be carefully computed. This is done by a group of engine experts called the "Engine Review Organization (ERO) (13:17)." This organization is a sub-committee of the USAF Propulsion Management Committee (PMC). The PMC's main function is to "address propulsion logistics support issues (13:16)." There is an ERO for each engine type, and ad-hoc meetings are set up to update and compute mature engine factors. These ERO's are chaired by the command with program management responsibility (AFSC during acquisition, and AFLC after PMRT) (13:17). This organization has the responsibility to keep a master file as a history for the engine type until it is retired (13:44). ERO meetings are held as needed, generally on an annual basis, and are attended by personnel from various ALC's, AFLC, ASD/YZ (the Propulsion SPO), MAJCOM representatives, and the engine manufacturer (13:18).

To estimate future factors this group considers many things. First they consider operational needs, those things

needed to perform mission objectives. They also look at r&m data and trends, military or commercial experience with the engine model, support concepts, and engineering analysis (13:45). The ERO must also estimate the effects of Engineering Change Proposals (ECP's), and compare similar engine models in an effort to forecast the mature engine factors (13:45). This effort is much more complex than the collection of the actual engine factors, and is an important step in the estimation of future costs and requirements.

Documentation for mature engine factors is also more detailed than for actual factors. In addition to documenting the factors, any assumptions used should also be noted (13:49). This provides a type of audit trail for future groups. It also allows the group to compare actual values later in an effort to determine the accuracy of these assumptions. The group is also required to summarize any changes from previous factors, and provide substantiation for the changes (13:45). Once computed, the PMC must review and approve the factors and changes before the data can be used to estimate future costs or requirements (13:46).

Tailoring SOSCM

The "Super Operating and Support Cost Model" was developed by ASD/YZLR to estimate costs for engines in full scale development and production phases of the acquisition

process. The model uses Logistic Support Cost Model equations, tailored for Air Force engines, to accomplish this very complex task (1:1). The model must consider both mature and actual engine factors, and be able to adapt to a variety of engines and maintenance concepts. This can result in an almost infinite number of variations due to the unique design of each engine model and the differences in the division of tasks discussed earlier. There are also differences in parts costs, repair times, and reliability rates. The bottom line is that the model must be flexible enough that the user can tailor it to the unique aspects of a wide variety of engine models and maintenance concepts found in the Air Force.

To allow the user to differentiate between two, three, and modified three level maintenance concepts SOSCM has a few different features. First, the user can input the number of bases and Jet Engine Intermediate Maintenance Shops (JEIMS). If the number of JEIMS equals the number of bases (i.e. there is an I-Level shop at every operating location) SOSCM models three levels of maintenance. If the number of JEIMS is zero there are no intermediate shops and a two level concept is modeled. Any number of JEIMS between zero and the number of bases results in a modified three level concept (1:14). Further detail is provided in the determination of initial spares. For a three level concept four elements are added to compute the

total number of initial spares. These are: base spares (including I-level spares), depot spares, production year number one condemnation spares, and production year number two condemnation spares. For a modified three level concept one other element is added. This is the number of JEIMS spares. SOSCM also assumes that some repair work is done at the JEIMS. For a two level concept, the base spares does not include I-level spares, and the model assumes there are no JEIMS facilities available. All items are assumed to be removed at O-level and all repairs done at the depot (1,2-4).

SOSCM also lets the user tailor the various pipeline times. This is done by providing inputs to base and depot repair cycle times and other logistics support factors in Table 1 (pg 5). Actual or mature engine factors can be input. The model also provides an option to use default values for LRU and SRU repair cycle times in accordance with AFLCP 173-10 (1:3). Support equipment costs are handled in a similar fashion, allowing the user to input a specific factor (percent of unit cost) or providing a default of 4.2% (1:6).

The "Engine O&S Input Matrix" provides the capability to enter specific engine data and divide the repair tasks for each component. This allows SOSCM to be tailored to the unique aspects of each engine model and its maintenance concept. For each component a code is entered to let the

model know whether the component in an engine, LRU, SRU, or "other (1:8)." The work sent to the depot is input for each component in ratio form, "item or event/total quantity removed." The remaining work is assumed to be done at the intermediate level (1:8). This feature allows the user to tailor SOSCM so that, for example, 20% of the exhaust work and 70% of the fan repairs are done at the depot. Engine, LRU, and SRU removal rates, maintenance man-hours per event (base and depot) and prices for any consumables are also input for each component. All of these features are included to give the user the flexibility to tailor SOSCM to the specific engine type and maintenance concept.

Life Cycle Cost (LCC) For Turbine Engines

The estimation of LCC for turbine engines is an extremely complex task. Many attempts have been made to identify, categorize, and model these costs. To understand all that this task encompasses it is first important to to provide a definition of LCC. One simplified definition is that "the life-cycle cost of an aircraft turbine engine is the sum of all elements of acquisition and ownership costs (26:9)." For the Air Force this definition can be expanded to include all phases of the acquisition process. These are concept definition, demonstration / validation, full-scale development, production, operation, and even disposal (7:3).

To create and use an accounting model, like SOSCM, to estimate these costs requires a variety of data. Not only is the accuracy of the data important, but it must also be compatible with the model being developed (26:11). A number of models have been developed without taking this into consideration. One study provided examples of two separate models that classified maintenance in unique ways. Unfortunately neither model could be used to estimate costs for Air Force engines because the Air Force does not collect data in a form that is compatible with either set of classifications required by the models (2:33-34). To sum it up, a life cycle cost model must be compatible with the data collected. It must also be capable of using this data to estimate costs throughout all phases of the life of the system.

The research done by Baker and Johnston attempted to classify operations and support costs for turbine engines in a way compatible with the form in which the Air Force collects the data. This research resulted in a breakdown of costs which could be used as a guide when developing a cost model for Air Force turbine engines. Their cost breakdown is shown in Table 2. Following the table is a brief description of each of the cost elements.

Table 2.

Air Force Operations and Support Costs (2:35)

- Base Level Maintenance
    - Material
        - Spare Parts
        - Expendable Material
    - Labor
    - Overhead
    - Transportation Expense of Items Sent to the Depot
- Depot Level Maintenance
    - Government Maintenance
        - Materials
            - Spare Parts
            - Expendable Supplies
            - Modification Kits
        - Labor
        - Overhead
    - Contractor Furnished Maintenance
- Component Improvement Program (CIP)
- Fuel Costs
- Aerospace Ground Equipment (AGE)
- Spare Engine Costs
- Training Costs
- Data Costs

The first category, Base Level Maintenance Costs, consists of all labor and parts consumed in maintaining engines at the base (2:43). As mentioned earlier, this maintenance is often limited to the removal and replacement of controls and accessories, and the removal of whole engines being sent to the depot. On the other hand, the majority of the Depot Level Maintenance Costs come from the overhaul and repair of engines and accessories. Currently this type of maintenance is required after a specified number of flying hours has been reached regardless of how the engine is performing (2:58).

CIP costs include "performance enhancement and additional applications within a specific engine program as well as corrections of deficiencies, reliability and cost reduction improvements (26:18)." The next category is fuel costs. In their study this included oil costs. These costs depend on the mission profile, operational use, and the performance characteristics of the engine (2:84).

Following fuel cost is the Aerospace Ground Equipment costs. Paraphrasing Baker and Johnston's report, AGE is any required ground equipment needed to prepare and keep a system operational in its intended environment (2:79-80).

Spare engine costs are fairly self explanatory. It is interesting to note that these costs can account for over 20% of the total procurement cost of engines for the weapon system (26:21).

Training and data costs are shown last in the table. These costs are normally much less than many of the other costs mentioned, but are still significant. For this reason, these costs should also be included when developing a LCC accounting model (26:23).

A few cost elements have not been covered yet. SOSCM models more than the operation and support costs. It also includes the initial acquisition costs (28:24). These costs should include the costs for RDT&E, flight testing, tooling, and procurement of installed engines (26:10).

One study provided a variety of interesting findings concerning the LCC of turbine engines. These are:

> 1. Engine depot and base maintenance costs, not including fuel and attrition (in constant dollars) will exceed acquisition costs.
>
> 2. Depot costs alone will exceed acquisition costs.
>
> 3. As much money can be spent on engine CIP during operation as was spent to develop the engine to its initial model qualification.
>
> 4. If government improvement and whole spare engine costs are considered "ownership costs" then ownership costs constitute at least two thirds of total engine LCC.
>
> 5. There is a trend toward higher ownership costs due to depot costs.
>
> (26:42-43)

There are a couple of points to make concerning these findings. First, when estimating LCC, none of the costs discussed in this section should be discounted without fully understanding the implications. Also, when considering design tradeoffs, the effects on maintenance costs can not be ignored. A good model should be designed to incorporate the data mentioned in the form which the data is collected by the Air Force.

Verification and Validation of a Model

One important concern before using a model is whether the model is adequate for the study. A confidence in the model helps provide credibility to the results. Experts in the development of simulation models generally consider two things when determining a models credibility. These two factors, defined below, are verification and validation.

> "Verification refers to the comparison of the conceptual model to the computer code that implements that conception. It asks the question: is the model implemented correctly in the computer code? Are the input parameters and logical structure of the model correctly represented in the code (3:376-377)?"

> "Validation refers to the act of determining that a model is an accurate representation of a real system. Validation is usually achieved through the calibration of the model, an iterative process of comparing the model to the actual system behavior and using discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged to be acceptable (3:377)."

The two are easily confused, but are actually quite different. In general terms verification is a debugging process. The main question in verifying a model is whether the model code is operating correctly. Verification is internal to the model. Validation, on the other hand, focuses on the relationship between program performance and real world behavior. This is external to the actual coding (23:224).

Ideally the processes involved in verification and validation of a model should take place while the model is being developed (21:338). This is not possible in this case since the model has already been developed and is being used to estimate the operating and support costs for turbine engines. Verification of the SOSCM model would involve a study of the individual Logistics Support Cost Model Equations, as tailored for engines. The code of the model would be examined to insure that the calculations are being done correctly. This is a very detailed process, and is difficult after the model is already fully developed. Due to time constraints of this study, verification of the code will not be done. For the purposes of this study it is more important that the model adequately represents the environment it is modeling. For SOSCM this is the LCC for turbine engines. As mentioned earlier, determining the relationship between program performance and real world behavior is the focus of validation.

Prior to attempting to validate the model a few points should be understood. First, the purpose for using a model to simulate the real world is to learn something about the real world (27:247). Therefore, the detail needed in the model and its validation depends on what the user needs to learn. The next factor to consider is that a model is an "abstraction" of a system. As such it can not be expected to exactly duplicate the real world. The important thing is that the model represents all the aspects of the real world needed for the intended use (27:247; 24:116). Something that should also be noted is that there are a variety of ways to validate a model. Richard L. VanHorn lists a number of validation methods in rough order of decreasing value to cost ratios. The choice of which factors should be used to validate a model again depends on the intended use of the model and the detail needed in the study. In fact, seldom are all possible validation actions needed (27:248). This list, and a short description of each item, is shown below:

1. Face Validity - This aspect of validation is concerned with whether or not the model appears reasonable on its face to the model users and others knowledgeable about the real system being simulated.

2. Make use of existing research, experience, observation, and any other available knowledge to supplement the model.

3. Conduct simple empirical tests of means, variances, and distributions using available data.

4. Run "Turing" type tests. Here experts compare real data with the output of the model. Preferably, to increase rigor, this would involve several sets of data.

5. Apply complex statistical tests on available data.

6. Engage in special data collection. This would compliment the modeling experiment.

7. Run prototype field tests.

8. Implement the results with little or no validation.

(3:385; 27:249-257)

The final thing that should be remembered is that, as in the case of verification, ideally validation should be done while the model is being developed (21:338). In the validation process this is mainly concerned with the calibration of the model. Calibration is "the iterative process of comparing the model to the real system, making adjustments (or even major changes) to the model, comparing the revised model to reality, making additional adjustments, comparing again, and so on (3:383)." Obviously this is difficult after the model is fully developed. Since this study is more concerned with the relative costs of various alternatives than with the level of accuracy of a specific cost estimate, calibration will not be completed. Following the findings, though, some changes to the model may be recommended.

The main point in the literature appears to be concerned with the reasonableness of a model, whether the model can adequately portray the real world. The key to answering this question is in determining the needs of the particular study. For this study, therefore, the validation of the model will be dependent on the purpose of the research.

III. Methodology

Objectives

The research questions listed in Chapter I can be grouped into two primary goals, and the study divided to answer these groups of questions in stages. The first of these goals is to determine the utility of the Super Operating and Support Cost Model (SOSCM) for this study. This is the validation process. The first four research questions will be answered in this process. SOSCM is used to estimate LCC for Air Force turbine engines. The model, its inputs, outputs, and assumptions will be considered. An assessment of the usefulness of SOSCM for this study will be made. The strengths and weaknesses of the model will be noted. Potential improvements to the model will be recommended, but no changes will be incorporated.

In the next stage, SOSCM will be used to determine the cost drivers for the three different maintenance concepts. These cost drivers will be compared in an attempt to understand how, in some cases, a three level concept can result in lower costs. This will allow ASD/YZ to choose a maintenance concept with increased confidence and understanding. These results will also have another use. Understanding the cost drivers will help Air Force personnel in their attempts to lower costs

by highlighting areas of focus for future cost cutting efforts.

Validation of the Cost Model

To achieve the first main objective of the research a literature review was completed to provide some vital information. First, SOSCM and its handbook were examined to determine the process used to compute LCC, the inputs needed, outputs provided, and assumptions made. The review also provided information concerning actual maintenance practices for various maintenance concepts. Next the engine factors used to estimate LCC for turbine engines, the role of the "Engine Review Organization" in the verification of these factors, and the ability to tailor SOSCM to accommodate the variety of concepts and factors were examined. In addition to this information, previous research was examined in an effort to determine the elements that need to be considered in an accounting model, like SOSCM, in order to estimate LCC.

The final section of the literature review ties all of the above information together. This section examines methods used to validate and verify models. Since this study is concerned with the use of an existing model the verification of the functioning of the code, which normally occurs while developing a model, will not be completed.

For the purposes of this research the concern is whether the model adequately represents the real world. In this case the "real world" is the LCC for turbine engines. Another concern is whether the model allows the user to analyze cost drivers for the different maintenance concepts. Model validation deals with these questions.

A number of validation methods, in decreasing order of utility to cost, were provided in the review. This list, according to the author, was provided as a type of menu. The choice of a method(s) to be used is dependent on the needs of the study (27:248). The use of the model in this study is to determine the cost drivers for the various maintenance concepts. It is not important that the model be able to estimate LCC within a given range, but that the model be able to distinguish between the costs for the different maintenance concepts. It should be able to input all significant cost elements needed to determine LCC for engines. The model also needs to allow a user to manipulate inputs, and examine outputs, in an effort to determine the cost drivers for each concept.

For these purposes, and with the information available, the second validation technique appears to best answer these questions. Determining face validity would involve surveying of experts, and questioning them about the model. Unfortunately, there are only a few persons who understand

the capabilities of this model. These are the logisticians who run the model in ASD/YZL. The population is not great enough to achieve significant results. The "Turing" test, having experts compare real data with the model output, is done regularly by the "Engine Review Organizations." The statistical tests would require numerous sets of data, not readily available, and the prototype field test is not easily applied to this study. The second method suggests comparing results from previous research to the model. For this study the research in the literature review, described earlier, will be compared with the capabilities of the model. By validating the model in this way not only can you determine whether it is a reasonable representation of the real world, but the strengths and weaknesses of SOSCM can also be examined. This is essential to the interpretation of the results of the modeling.

Analysis of the Cost Drivers

In this stage of the study SOSCM will be used to determine the cost drivers for each of the three maintenance concepts. The sensitivity of LCC for each cost driver will also be examined. The inputs to the model will be collected from actual engine data. Due to the large quantity of data needed per engine, and the complexity of the model, only one engine will be modeled.

To do all of this the data will be collected, the input matrix formed, and the model run to estimate costs for three levels of maintenance. This will provide a baseline case. The input matrix will then be modified by reducing the number maintenance levels from three levels of maintenance (12 JEIMS), down to a modified three level concept (2 and 1 JEIMS), then to two levels (0 JEIMS). For each case the model will be run, and the changes documented.

The outputs will be analyzed in an effort to determine which elements drive the costs in the various maintenance concepts. This will provide insight into the LCC implications of moving to two levels of maintenance.

Next a sensitivity analysis will be completed. Again the baseline case will provide a starting point. From there one input variable will be manipulated, and the number of JEIMS reduced from 12 to 2, 1 and finally 0 in an effort to understand the effects of the changes on each maintenance concept. This procedure will be repeated for a range of inputs for all elements tested. The effects of these changes on LCC will then be analyzed. The whole process will be repeated for a variety of cost elements.

The results from this research will consider the strengths and weaknesses of the model found in validation. These results can be useful in a number of ways. Not only

can the sensitivities be determined, but this study may also point out which cost elements to focus on in efforts to lower the LCC for turbine engines. This research will also provide some insight into the cost implications of moving to a different maintenance concept for an engine model.

IV. Modeling and Analysis

Model Validation

Two major factors will be considered when determining the usefulness of SOSCM for this study. The first is the ability of SOSCM to estimate LCC. To determine this, the capabilities of SOSCM will be compared to the cost elements noted in Chapter II. The elements should be incorporated in an accounting model to reasonably estimate life cycle cost (LCC). Next, the capabilities of SOSCM will be examined to determine its ability to handle the special needs of this study. For example, one goal of this study is to determine some of the cost factors which may impact the choice of a maintenance concept for an engine. By examining these points the strengths and weaknesses of the model will be understood. This will allow better analysis of the results.

Estimating LCC. The information collected in the literature review provided a number of elements which need to be incorporated in an accounting model to reasonably estimate LCC. To summarize, the elements in Table 2 should be considered. In addition, the initial acquisition costs should be included. If any of these factors are missing, they should be analyzed to determine the possible effects on the results.

Requirements of the Study. This study places a few requirements on the model. One of these is the ability to manipulate the model so that the costs of two, three, and modified three level maintenance concepts can be estimated. Another capability the model must have is the ability to vary the inputs so that the effects of changes in inputs on LCC can be examined. Another necessary characteristic of the model deals with the output. The output must divide the costs into a variety of categories so that the cost changes can be broken down and related to the changes in inputs. This will allow a more in depth analysis of the various cost changes.

SOSCM Strengths and Weaknesses. To analyze the capabilities of SOSCM to reasonably estimate LCC, the first thing that will be done is to compare the cost elements needed in an accounting model (Table 2) to SOSCM's Standard Factors (Table 1).

The first element in Table 2 is Base Level Maintenance costs. This includes materials (spare parts and expendable materials), labor, overhead, and transportation expense of items sent to the depot. Looking at Table 1, there are a few factors used to calculate Base Level Maintenance. These include the number of bases and JEIMS under the Operational Concepts Factors. The base material rates, labor rates, and spares factors are included in the Logistics Support

Factors and Standard Cost Factors. Shipping and packaging rates are also under this category. There is also an input for pipelines spares factors. The input of overhead costs, though, is more difficult. Direct overhead, like the cost of supervision, can be included in the labor cost. Indirect overhead, which would include things like maintenance of the base facilities, is not easily input. In fact, it is stated in Table 1 that the annual base supply management costs are not used in the model.

The next element is Depot Level Maintenance. This is broken down into government and contractor furnished maintenance. Government furnished maintenance includes materials (spares parts, expendable supplies, and modification kits), labor, and overhead. SOSCM has inputs for all of these except, again, overhead. Like base level maintenance direct overhead must be included in the labor rates, and no input exists for indirect overhead. The model also does not allow the user to divide government and contractor furnished maintenance.

The model has no input for component improvement program (CIP) costs. These costs must be included in the procurement or maintenance costs. Since CIP costs would be required regardless of the maintenance concept this should have little effect on this study.

Fuel costs are included. Inputs are available for fuel efficiency (Gallons/Engine Flying Hour), utilization rate (Hours/Month), and actual fuel cost ($/Gallon).

There are a number of inputs for Aerospace Ground Equipment (AGE). These are in the form of various support equipment costs. The number and cost of spare engines can be input, or the model can estimate the number of spares needed.

The final elements in Table 2 are Training and Data costs. The model does not have inputs for these elements. In fact, as mentioned in Table 1, the handbook specifically notes that data costs are not used in the model. This should have little impact on the cost difference between the various maintenance concepts. Although there would be additional training and copies of technical data to go along with the added number of JEIMS in a three level (vs. a modified three or two level concept) the cost of developing the data and training methods would be the same. Overall, the cost savings of a two level concept may be slightly underestimated due to this.

There are a number of other capabilities needed for this study. One is the ability to estimate costs for different maintenance concepts. As mentioned in Chapter II, SOSCM can be tailored to do this. One weakness should be mentioned. Economies of scale was one of the

reasons given for moving to two levels of maintenance. SOSCM does account for the economies of scale by adjusting the number of spares needed to satisfy the demands for each maintenance concept. It does not cover the savings which would be realized by ordering large quantities of items from a single maintenance location. Again this could underestimate the savings found when moving to a two level maintenance concept.

The model does provide a wide range of costs in its output which makes it possible to analyze the cost changes and relate them to the input changes. The model also has a sensitivity analysis function. This lets a user vary individual inputs on the screen.

Summary. The key to analyzing the strengths and weaknesses of SOSCM is to keep in mind the intended use of the model. In this study the model is being used to point out cost differences for the various maintenance concepts. Although all of the weaknesses are important, the main concern is the effect on the ability to differentiate between costs from one concept to another.

Neither base nor depot overhead costs are broken out separately in the model. To input them they must be included in the labor rates. According to the information in the literature review, base and depot maintenance cost are major factors in the LCC of engines.

Overhead, though, was never mentioned as a major portion of these costs. Not including these may reduce cost savings slightly when moving from three to two levels of maintenance. This is due to the fact that overhead at more than one base shop would be saved. Depot costs may increase with the increased work load, but it is unlikely the increase would equal the savings from the reduction of JEIMS.

The inability to separate government and contractor furnished maintenance costs should have little or no effect on the study. These can be combined and input as government furnished maintenance costs.

The literature does state that CIP costs can be significant. In fact, these costs can actually equal the development costs. Impro ement costs, though, would be the same regardless of the maintenance concept, and should have little effect on the results of this study. Similarly, training and technical data costs, although significant, will only differ slightly from three to two levels of maintenance due to the change in volumes needed. Again, savings from moving to two levels of maintenance may be slightly underestimated because of this.

Another deficiency is the lack of any way to account for the economies of scale in spare parts and materials ordered from a single location. Economies of scale is

one of the major factors used to support the move to two levels of maintenance. Not incorporating these savings could reduce the savings shown by the model. SOSCM does adjust the number of spares needed though. This may account for a large part of the impact from the economies of scale. Because of this, the deficiency may not be major, but again may underestimate the savings achieved when moving to a two level maintenance concept.

Overall the deficiencies of SOSCM appear to reduce some of the possible savings when moving from three to two levels maintenance. Alone many of these effects may be small, but combined they could be significant. This will be considered when using the model and analyzing the results.

Modeling

Description of the Test Case. A test case was provided by ASD/YZ to conduct the modeling experiment. The case is generic. It contains no proprietary information, and is intended to reasonably represent a modern turbine engine.

The details of the case are provided in Tables 3-7. These tables are broken out from the standard factors found in Table 1. Highlights of the case include a 25 year life cycle. The first 5 are production years. There

are 222 engines, plus spares, purchased in these years. The number of spares is estimated by the model or input by the user. Table 7, Supplementary Factors, shows an initial value of 29 spare engines. This is the number calculated by the model for the baseline case, a full three level maintenance concept. The number estimated varies for other concepts. The final 20 years are steady state, operational, years. There are 12 bases, all conus, and, as explained earlier, the numbers of intermediate level shops (JEIMS) will vary from 12 (three levels of maintenance) to 0 (two levels of maintenance. No information was available to estimate the cost of support equipment. Other factors are shown in the tables.

Table 3. Program Definition Factors

Number of Production Years	5
Number of Steady State Years	20
Total PAA Engines	222

Table 4. Operational Concept Factors

Number of Bases	12
Number of JEIMS	12
Utilization Rate (Hrs/Mo)	26.45
Percent of Fleet in CONUS	100
Fuel Utilization (Gal/EFH)	800.00

Table 5. Standard Cost Factors

Fiscal Year Dollars	86
Base Labor Rate ($/Hr)	31.26
Base Material Rate ($/Hr)	6.09
Depot Labor Rate ($/Hr)	61.74
Depot Material Rate ($/Hr)	35.43
Fuel Cost ($/Gallon)	0.94
Packaging Rate ($/Lb)	2.81
CONUS Shipping Rate ($/Lb)	0.48
Overseas Shipping Rate ($/Lb)	2.17
Part Number Introduction Cost *	1200.00
Part Number Annual Management Cost *	162.39
Annual Base Supply Management Cost *	11.14
Tech Data Acquisition Cost ($/pg) *	696.52
Tech Data Update Cost ($/pg) *	185.70
Tech Data Repro Cost ($/pg) *	0.01

* Not currently used in the model

Table 6. Logistics Support Factors

	LRU	SRU	ENG
Base Repair Cycle Time (Days)	6	8	12
Depot Repair Cycle Time CONUS (Days)	43	50	58
Depot Repair Cycle Time OS (Days)	51	58	65
Order and Ship Time CONUS (Days)	10	10	10
Order and Ship Time OS (Days)	15	15	15
Auto. Resupply Time CONUS (Days) *	10	10	10
Auto. Resupply Time Overseas (Days) *	15	15	15
Spares Confidence Factor	1.65	0.85	0.85
Item Weight/Packaged Weight Ratio			1.941
Recurring Support Equip. Cost (% of Unit cost)			0.042

* Not currently used in the model

Table 7. Supplementary Factors

Whole Engine Spares (Quantity)	29
Support Equipment (M$)	
Common	0.00
Peculiar	0.00

Tables 3-7 outline the standard factors for the engine. There is other information needed, though, for the model to estimate LCC. This information describes the design characteristics of the engine and its components. This data includes the maintenance event rates, removal rates, Not Repairable This Station (NRTS) rates, and the estimated maintenance manpower per event (MMH/Event). The data must also provide information on the cost of the engine and its components, and the cost of consumables and condemned parts per event. The model also needs inputs for unit weight, and quantities of each part per engine. This data is presented in Tables 8-11.

Two vs. Three Levels of Maintenance. The first case run was the baseline case. There were twelve JEIMS and the model estimated the number of spare engines needed to be 29. At a cost of $2M/engine this translates to a cost of $58 million. Using the inputs, the model estimated a total of 1,530,848 engine flying hours for the life of the program.

Table 8. Engine and Component Rates

ITEM/EVENT	CODE (LRU,SRU, ENG)	Maint. Event Rate	Removal Rates ENG	Removal Rates LRU	NRTS Rate
ENGINE	E	5.00	5.00	0.00	0.08
FAN	S	1.30	1.20	0.00	0.30
ROTOR	S	1.30	1.20	0.00	0.50
STATOR	S	0.20	0.20	0.00	0.30
HPC	S	0.90	0.40	0.00	0.40
ROTOR	S	0.50	0.20	0.00	0.60
STATOR	S	0.20	0.20	0.00	0.30
COMBUSTER	S	0.60	0.30	0.00	0.10
HPT NOZZLE	S	0.60	0.50	0.00	0.40
COMBUSTION LINER	S	0.30	0.20	0.00	0.80
HPT	S	0.60	0.50	0.00	0.30
ROTOR	S	0.60	0.50	0.00	0.60
LPT	S	0.70	0.60	0.00	0.10
ROTOR	S	0.90	0.90	0.00	0.80
NOZZLE	S	0.80	0.80	0.00	0.90
SYSTEM	S	0.30	0.20	0.00	0.10
OTHER ENGINE	S	3.00	0.20	0.00	0.01
MAIN FUEL PUMP	L	0.21	0.00	0.21	1.00
MAIN FUEL CONT.	L	0.63	0.00	0.63	1.00
CONTROL ASY., ELECTRICAL	L	0.40	0.00	0.35	1.00
AB FUEL PUMP	L	0.20	0.00	0.10	1.00
AB FUEL CONTROL	L	0.20	0.00	0.20	0.90
VEN POWER UNIT	L	0.40	0.00	0.29	1.00
VEN OIL FILTER	L	2.00	0.00	2.00	0.00
IGNITION EXCITER	L	0.26	0.00	0.25	1.00
REDUNDANT IG. EXCITER	L	0.10	0.00	0.02	1.00
ANTI-ICING VALVE	L	0.30	0.00	0.30	0.20
OIL TANK ASY	L	0.14	0.00	0.14	0.50
FUEL FILTER	L	2.00	0.00	2.00	0.00
SPRAYBARS	L	0.10	0.00	0.03	0.00
VEN FLAPS and SEALS	L	0.15	0.00	0.14	0.10
THERMOCOUPLE HARNESS	L	0.44	0.00	0.41	1.00
AG IGNITER PLUG	L	3.00	0.00	2.00	0.00
OTHER CONTROLS	L	2.00	0.00	1.67	0.70

Table 9. Manpower Requirements

ITEM/EVENT	MMH/Event Base	MMH/Event Depot
ENGINE	14.00	1143.00
FAN	28.00	69.00
ROTOR	69.00	620.00
STATOR	89.00	636.00
HPC	21.00	500.00
ROTOR	55.00	454.00
STATOR	46.00	123.00
COMBUSTER	25.00	172.00
HPT NOZZLE	35.00	137.00
COMBUSTION LINER	42.00	345.00
HPT	18.00	742.00
ROTOR	58.00	247.00
LPT	28.00	754.00
ROTOR	82.00	543.00
NOZZLE	65.00	184.00
SYSTEM	15.00	3245.00
OTHER ENGINE	28.00	82.00
MAIN FUEL PUMP	1.00	35.00
MAIN FUEL CONT.	1.00	179.00
CONTROL ASY., ELECTRICAL	1.00	243.00
AB FUEL PUMP	1.00	54.00
AB FUEL CONTROL	0.90	86.00
VEN POWER UNIT	1.00	24.00
VEN OIL FILTER	0.00	165.00
IGNITION EXCITER	1.00	0.00
REDUNDANT IG. EXCITER	1.00	0.00
ANTI-ICING VALVE	0.20	14.00
OIL TANK ASY	0.50	15.00
FUEL FILTER	0.00	0.00
SPRAYBARS	0.00	23.00
VEN FLAPS and SEALS	0.10	277.00
THERMOCOUPLE HARNESS	1.00	86.00
AG IGNITER PLUG	0.00	0.00
OTHER CONTROLS	0.70	26.00

Table 10. Unit Prices

ITEM/EVENT	% Unit Price Consum./Event) Base	Depot	% Unit Price (Cond./Event) Base	Depot	Unit Price
ENGINE	0.00	0.3	0.00	0.06	2000000
FAN	0.01	0.6	0.00	0.00	12345
ROTOR	0.10	0.10	0.00	0.01	19735
STATOR	0.10	0.10	0.00	0.01	12345
HPC	0.10	0.04	0.00	0.00	23456
ROTOR	0.01	0.25	0.00	0.02	45678
STATOR	0.03	0.11	0.00	0.02	901234
COMBUSTER	0.00	0.39	0.00	0.00	567890
HPT NOZZLE	0.10	0.00	0.00	0.50	243657
COMBUSTION LINER	0.00	0.00	0.00	0.02	789456
HPT	0.10	0.17	0.00	0.00	110040
ROTOR	0.01	0.24	0.00	0.02	138000
LPT	0.00	0.06	0.00	0.00	160000
ROTOR	0.00	0.10	0.00	0.02	72000
NOZZLE	0.00	0.00	0.00	0.67	45000
SYSTEM	0.01	0.30	0.00	0.00	100000
OTHER ENGINE	0.01	0.02	0.00	0.00	300000
MAIN FUEL PUMP	0.00	0.07	0.00	0.02	150000
MAIN FUEL CONT.	0.00	0.05	0.00	0.02	155000
CONTROL ASY., ELECTRICAL	0.00	0.06	0.00	0.09	180000
AB FUEL PUMP	0.00	0.30	0.00	0.02	45000
AB FUEL CONTROL	0.01	0.02	0.00	0.02	40000
VEN POWER UNIT	0.00	0.04	0.00	0.02	45000
VEN OIL FILTER	0.20	0.00	0.00	0.00	1234
IGNITION EXCITER	1.00	0.00	0.00	0.00	4500
REDUNDANT IG. EXCITER	1.00	0.00	0.00	0.00	3900
ANTI-ICING VALVE	0.00	0.30	0.00	0.05	4888
OIL TANK ASY	0.09	0.00	0.00	0.02	8888
FUEL FILTER	0.26	0.00	0.00	0.00	250
SPRAYBARS	0.12	0.00	0.00	0.00	3699
VEN FLAPS and SEALS	0.00	0.00	0.00	0.80	1400
THERMOCOUPLE HARNESS	0.00	0.00	0.00	0.90	2589
AG IGNITER PLUG	0.26	0.00	0.00	0.00	500
OTHER CONTROLS	0.01	0.01	0.00	0.00	100000

Table 11. Item Weights and Quantities

ITEM/EVENT	Bare Weight	Quantity Per Engine
ENGINE	5000	1
FAN	1000	1
ROTOR	500	1
STATOR	100	1
HPC	200	1
ROTOR	50	1
STATOR	50	1
COMBUSTER	500	1
HPT NOZZLE	1500	1
COMBUSTION LINER	100	1
HPT	100	1
ROTOR	100	1
LPT	200	1
ROTOR	100	1
NOZZLE	100	1
SYSTEM	22	1
OTHER ENGINE	4	1
MAIN FUEL PUMP	22	1
MAIN FUEL CONT.	22	1
CONTROL ASY., ELECTRICAL	22	1
AB FUEL PUMP	22	1
AB FUEL CONTROL	22	1
VEN POWER UNIT	22	1
VEN OIL FILTER	22	1
IGNITION EXCITER	22	1
REDUNDANT IG. EXCITER	22	1
ANTI-ICING VALVE	22	1
OIL TANK ASY	22	1
FUEL FILTER	22	1
SPRAYBARS	22	6
VEN FLAPS and SEALS	22	12
THERMOCOUPLE HARNESS	22	1
AG IGNITER PLUG	22	1
OTHER CONTROLS	22	1

The number of JEIMS was reduced to two, one, and zero. This lets the model estimate the costs for modified three level concepts similar to the C-17 program (2 JEIMS) and the KC-135R program (1 JEIMS). Zero JEIMS provides the LCC estimate for two levels of maintenance. The resulting life cycle costs, in millions of dollars, are summarized in Table 12.

Table 12. LCC for Two vs. Three Levels of Maintenance

Life Cycle Cost (M$)	Number of JEIMS			
	12	2	1	0
Spare Engines	58.00	78.00	80.00	160.00
Initial Spares	63.90	30.60	27.38	26.97
Condemnation Spares	177.20	177.20	177.20	177.20
Base Material	48.31	48.31	48.31	9.66
Base Labor	16.92	16.82	16.82	3.36
Depot Material	444.53	444.53	444.53	483.18
Depot Labor	250.70	250.70	250.70	277.29
Second Destination Transportation	38.10	279.39	303.52	289.55
Fuel	1151.20	1151.20	1151.20	1151.20
Totals:	2248.77	2476.76	2499.66	2578.41

There are a few things to note about these results. First, as the model moved toward two levels of maintenance the number of spare engines needed increased from 29 to 80 ($58 to $160 million). The initial spares decreased though. This decrease was enough that the total cost for spares (engines + initial + condemnation) decreased

through a modified three levels concept with one JEIMS. The number of spare engines, though, doubled from one JEIMS to zero. The decrease in initial spares cost was not enough to make up for this increase. These changes are shown in Table 13.

Table 13. Spares Costs (M$)

	JEIMS 12	2	1	0
Spare Engines	58.00	78.00	80.00	160.00
Initial Spares	63.90	30.60	27.78	26.97
Condemnation Spares	177.20	177.20	177.20	177.20
Total:	299.10	285.80	284.58	364.17

It is also interesting to note that base and depot labor and material was unchanged until the number of JEIMS was reduced to zero. This can be explained by considering the tasks completed at each level. Although the number of JEIMS is fewer for a modified three level concept, the same tasks are still completed at the intermediate level. Some JEIMS have been eliminated, and others have increased loads. Overall, though, the total load at the intermediate level shops is unchanged. Similarly the load at the depot will also remain unchanged. This changes when the number of JEIMS is reduced to zero. At this point the intermediate level tasks are transferred to the depot.

Base material costs decreased from $48.31 to $9.66 million ($38.65 mil. decrease) when moving from three to two levels of maintenance. Depot material increased by the same amount, from $444.53 to $483.18 million. Labor costs at the base level decreased from $16.82 to $3.36 million ($13.46 mil. decrease). Depot labor costs increase from $250.70 to $277.29 million ($26.59 mil. increase). This is almost double the decrease in base labor cost. Looking at the Standard Cost Factors in Table 5, this difference is easily explained. The depot labor rate is approximately twice that of the base rate ($61.74 vs. $31.26 $/Hr). This may be due to the skill level needed to complete depot level tasks.

The second destination transportation costs increase greatly from three levels to the modified three levels due to the additional cost of shipping engines to the regional maintenance centers. The cost drops slightly from one to zero JEIMS, but this drop still leaves an increase from $38.10 to $289.55 million ($251.45 mil.) when moving from three to two levels of maintenance.

The final factor shown in Table 12 is fuel. Since the number of operating hours is independent of the number of JEIMS, the fuel costs were unchanged.

Total LCC increased gradually from 12-2-1-0 JEIMS. The total increase was from $2248.77 to $2578.41 million.

This is a total increase of $329.64 million. The cost changes are presented in Table 14. To simplify the results the base and depot labor and material costs are combined.

Table 14. Cost Changes (M$)

	Cost Change	% Total Change
Spare Engines	$102.00	30.9
Initial Spares	($36.93)	-11.2
Condemnation Spares	0.00	0.0
Material (Base and Depot)	0.00	0.0
Labor (Base and Depot)	$13.13	4.0
Second Destination Transportation	$251.45	76.3
Fuel	0.00	0.0
Totals:	$329.65	

Net Change $329.65 million (14.7% increase)

These results further highlight the impact of the changes in second destination transportation and spare engine costs. These factors are the major contributors to the LCC increase. Although overall labor costs did increase due to the higher labor rate, it only accounted for 4.0% of the total increase. Engine spares resulted in a 30.9% cost increase. Even if all spares cost changes are combined the increase is still $65.07 million ($102.00-$36.93). This is 19.7% of the net change. This change is still significant. The second destination cost increase is by far the most significant change. This factor accounts

for 76.3% of the total increase. Combined, the changes result in a 14.7% increase in costs from three levels of maintenance to two.

Sensitivity Analysis

A sensitivity analysis was completed in a effort to understand some of the cost drivers for the various maintenance concepts. The model allows the user to vary any of the factors in Tables 3-7. SOSCM also lets the user manipulate the specific engine information found in Tables 8-11. To make this easier a set of sensitivity multipliers is provided. The factors all have defaults of 1.0 and can be easily increased or decreased. These factors are listed in Table 15.

Table 15. Sensitivity Analysis Factors

Cost Factor	Default Value
Maintenance Event Rate Multiplier	1.00
Engine Removal Rate Multiplier	1.00
SRU Removal Rate Multiplier	1.00
LRU Removal Rate Multiplier	1.00
Parts NRTS Multiplier	1.00
Major Assembly NRTS Multiplier	1.00
Engine NRTS Multiplier	1.00
Base MMH/Event Multiplier	1.00
Depot MMH/Event Multiplier	1.00
Base Consumables Multiplier	1.00
Depot Consumables Multiplier	1.00
Base Condemnation/Event Multiplier	1.00
Depot Condemnation/Event Multiplier	1.00
Unit Cost Multiplier	1.00
Weight Multiplier	1.00

For this study a number of factors were varied. Due to the large number of combinations possible, an attempt was made to place an emphasis on factors which could have an effect on the drivers found in the first part of this study. These were the costs of engine spares and second destination transportation. Like the previous cases, the number of JEIMS input was 12, 2, 1, and 0 to estimate costs for three, modified three, and two level maintenance concepts. In this analysis SOSCM estimated the number of spare engines needed. Data for the runs is contained in Appendix A.

Maintenance Event Rate. The first factor considered is the maintenance event rate. The event rate multiplier was varied from 1.0 to 0.5 in increments of 0.1. the data is plotted in Figure 2. The baseline case is where the multiplier equals 1.0. The decreasing event rate results in a decrease in LCC. A 10% decrease in this rate causes approximately 3.5-4.0% cost reduction. The decreases appear to be linear. The cost curves for 12, 2, 1, and 0 JEIMS are approximately parallel. This means that the effect of reducing the event rate is nearly the same for all of the concepts examined. There is also no point in the figure where the life cycle cost for two levels of maintenance, with equal event multipliers, is lower than the LCC for three levels.

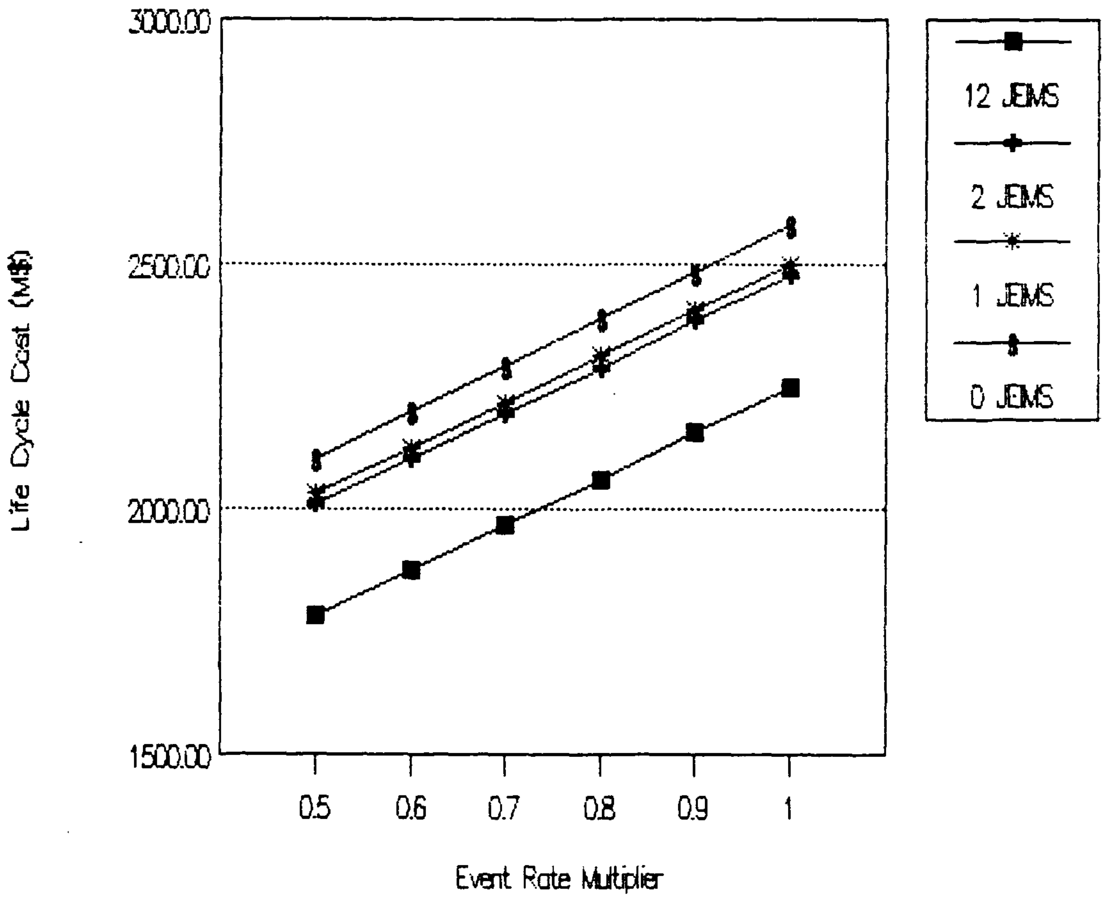

Figure 2. Maintenance Event Rate

Engine Removal Rate. The removal rate multiplier was varied from 1.0 to 0.1 by 0.1 to examine the effect of engine removal rate on LCC. The results are shown in Figure 3. In this case, the curves are not parallel, meaning that the effect depends on the maintenance concept. For a three level concept (12 JEIMS) a 10%

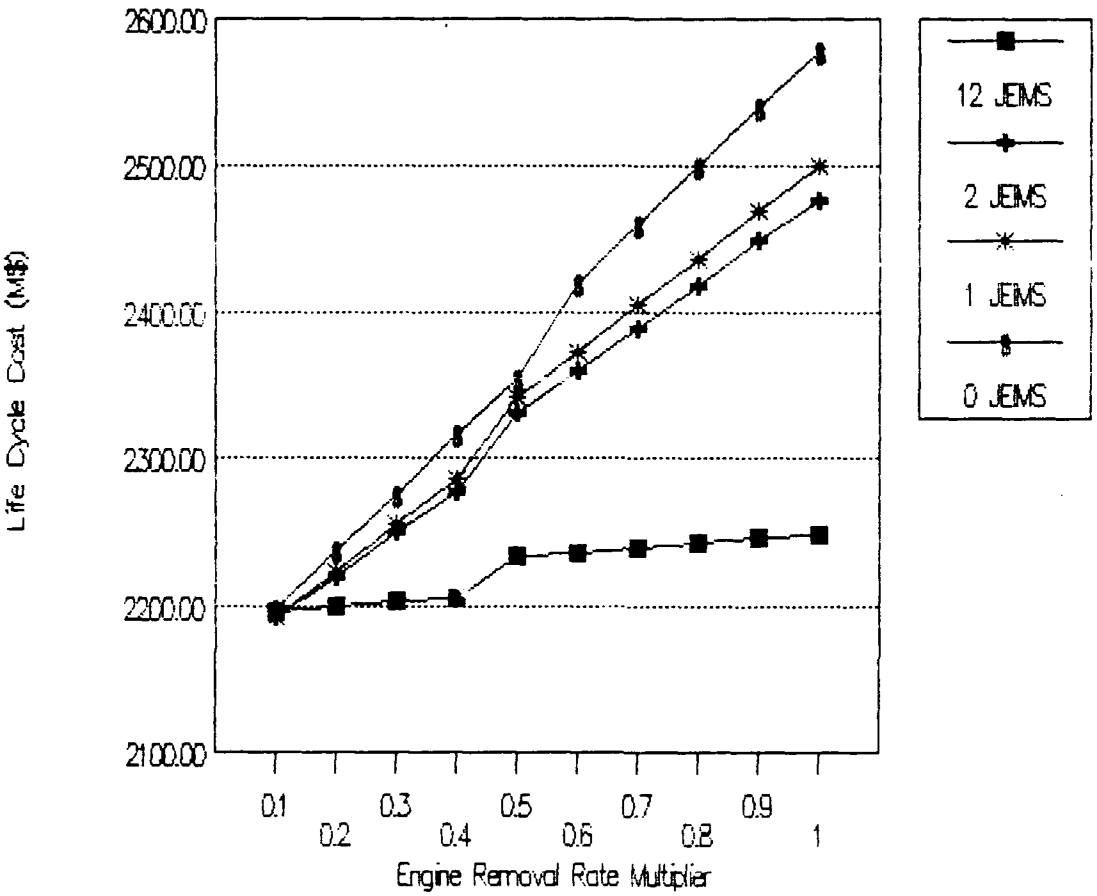

Figure 3. Engine Removal Rate

reduction in removal rate results in only a 0.1-0.2% decrease in LCC (approx. $2 million). A 10% reduction in removal rate for the modified three level concepts (2 or 1 JEIMS) results in a 1.2% decrease in LCC. This is nearly $30 million. For a two level concept (0 JEIMS) the same reduction results in 1.5-2.0% cost decrease. At

the extreme case, where the multiplier was 0.1, the cost is nearly equal for all concepts. One other thing should be mentioned. The curves appear linear except around a multiplier of 0.5. The cases were run repeatedly to check the data. The results were the same. This could be a flaw in the model, and may need to be corrected.

Engine NRTS Rate. The multiplier for the engine NRTS (Not Repairable This Station) rate was also varied

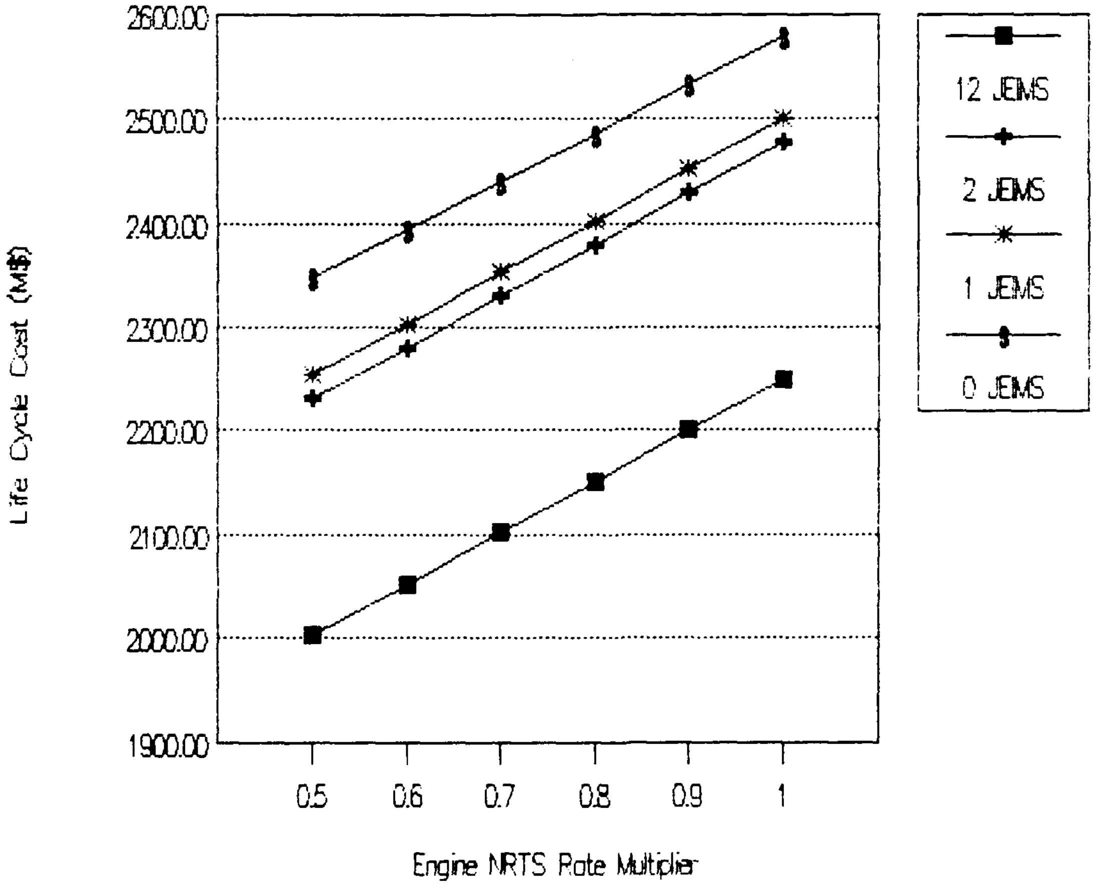

Figure 4. Engine NRTS Rate

from 1.0 to 0.5. Again the plots appear to be parallel. Looking at the data there is a slight difference depending on the maintenance concept. A 10% decrease in NRTS rate results in a 2.2-2.4% decrease in costs for a three level concept, 1.9-2.1% for the modified three level cases and 1.8-1.9% for two levels of maintenance.

<u>Base Maintenance Man-hours/Event</u>. The base MMH/event multiplier was varied like the other factors.

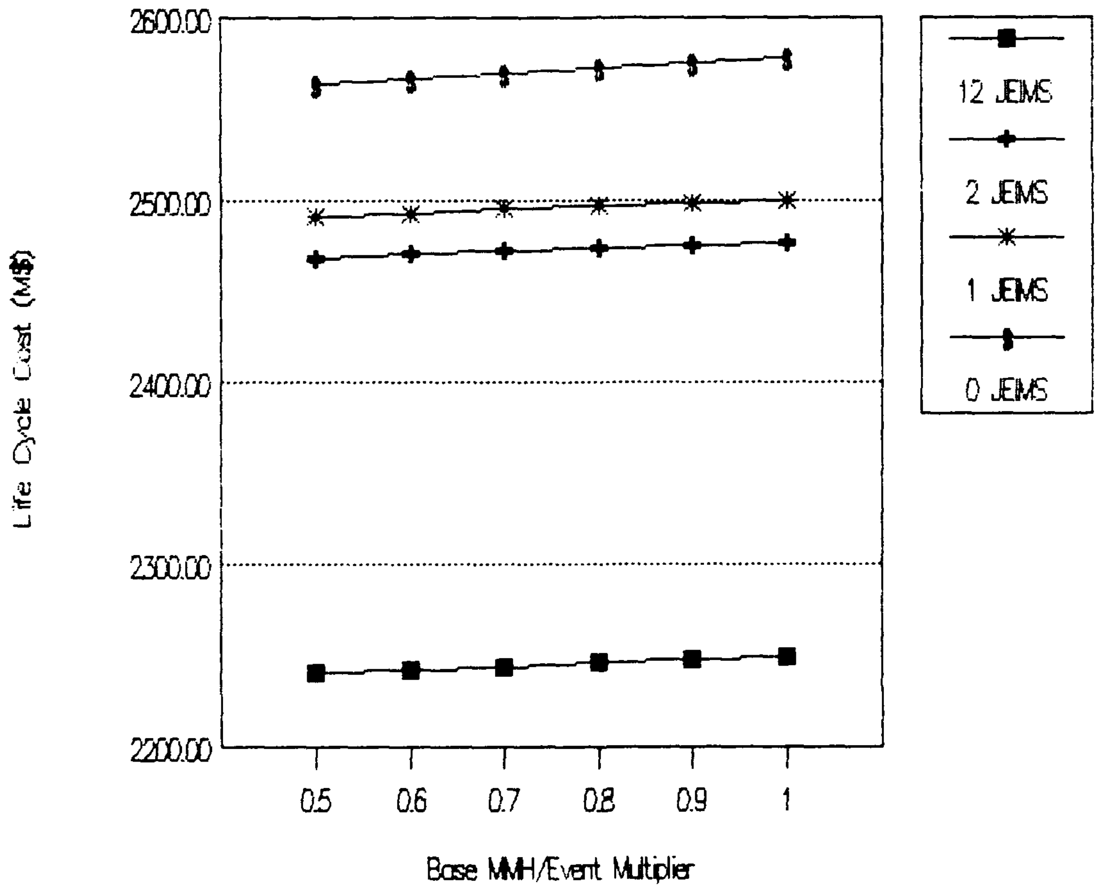

Figure 5. Base Maintenance Man-hours (MMH)/Event

The results are in Figure 5. Here the curves appear parallel. They also appear to be nearly horizontal. This would mean that reducing the base MMH/event has little effect on LCC. This is more obvious when looking at the data. There is only a 0.1% cost change per 10% reduction in MMH/event. This is true for all concepts.

Depot Maintenance Man-hours/Event. The same range of multipliers results in the curves shown in Figure 6.

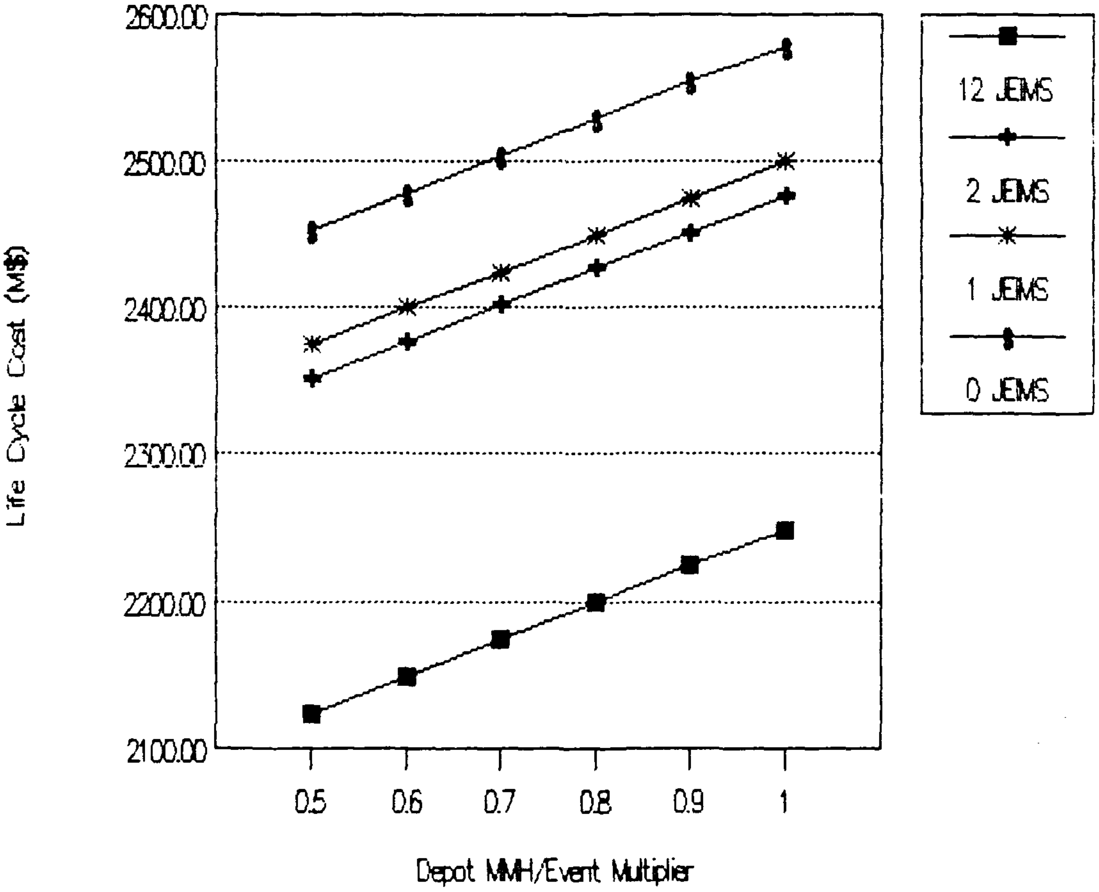

Figure 6. Depot Maintenance Man-hours (MMH)/Event

Reducing the depot MMH/event results in around 1.0% decrease in LCC for each of the concepts. This may not sound like much, but the savings would be approximately $25 million. The effects from reducing the depot MMH/event are greater than those seen from similar reductions in base MMH/event. This may be due to a number of things. First, the depot manpower rate ($/hr.) is almost double the base rate. Also, the tasks at the depot are more complex, and include engine teardown and overhaul. These task require more time. This can be seen in the repair cycle times found in Table 6. These facts result in depot repair costs being a greater portion of the total LCC. Reducing the depot MMH/event, therefore, would result in greater savings than the same reduction in base MMH/event.

Engine Cost. Next the engine cost was varied. This time, though, the multiplier ranged from 0.2 to 2.0 by 0.2 so that cost increases in engine price could also be examined. The effects are seen in Figure 7. One thing is obvious, as the number of JEIMS is reduced from 12 to 2 or 1 and then to 0 the effect of a change in engine cost has a greater effect on LCC. The curves become steeper due to the increase in the number of spare engines required as the number of JEIMS is reduced, as mentioned in the baseline case.

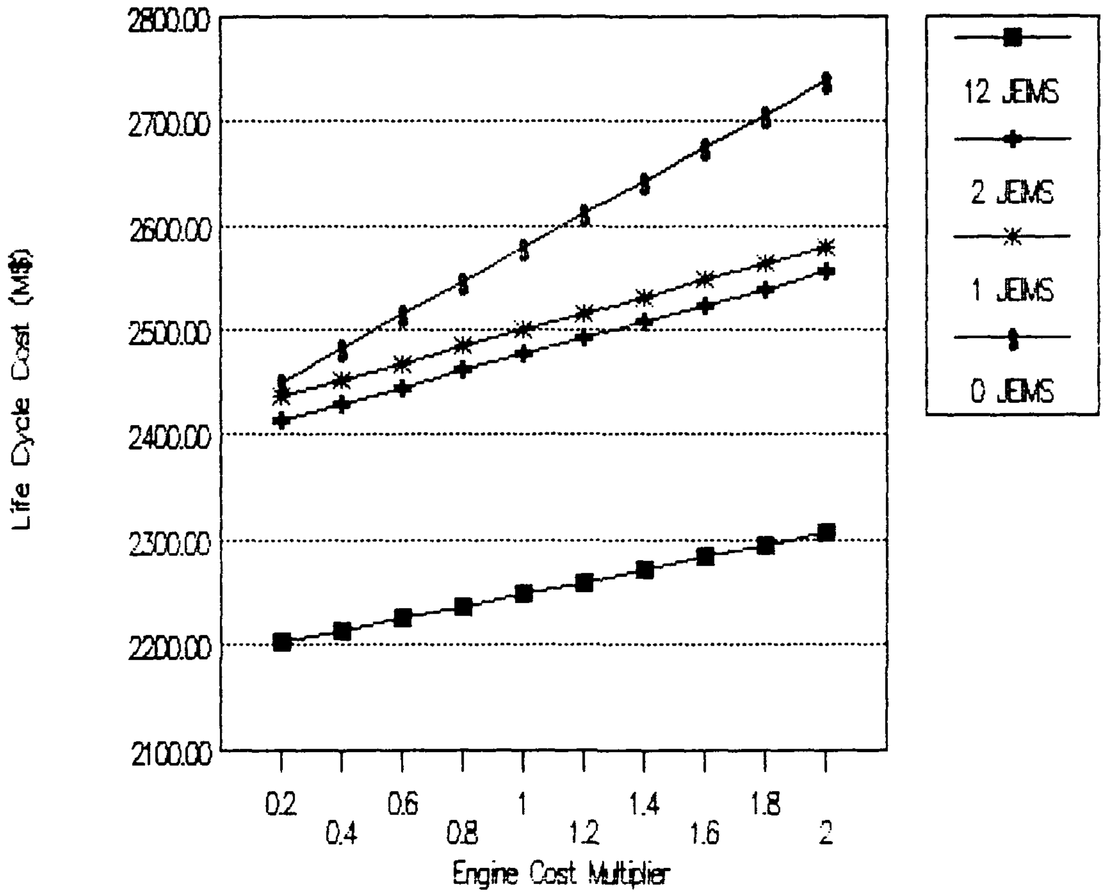

Figure 7. Engine Cost

<u>Engine and Other Unit Costs</u>. Figure 8 shows the effects of varying the cost of the engine and other parts. Like the last section, the cost multiplier ranged from 0.5 to 2.0 so the effects of cost increases could also be seen. Again the changes had a greater effect on a two level concept than the three or modified three level concepts.

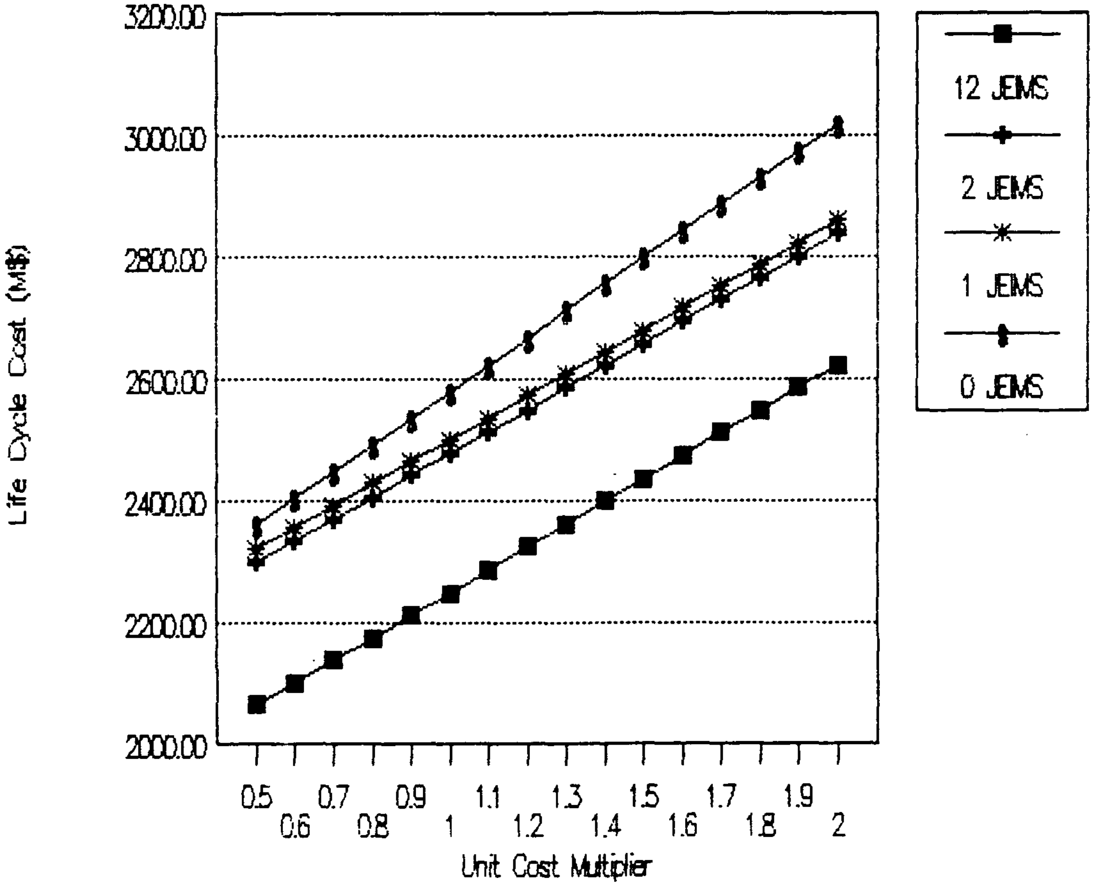

Figure 8. Engine and Other Unit Costs

<u>Shipping Rate</u>. The shipping rate was manipulated to provide information on the change in second destination transportation costs found in the baseline cases. The rate, found in Table 5, was 0.48 ($/lb.). There is no multiplier for shipping so the rate itself was varied from 0.24 to 0.48 by 0.04. The results are plotted in Figure 9.

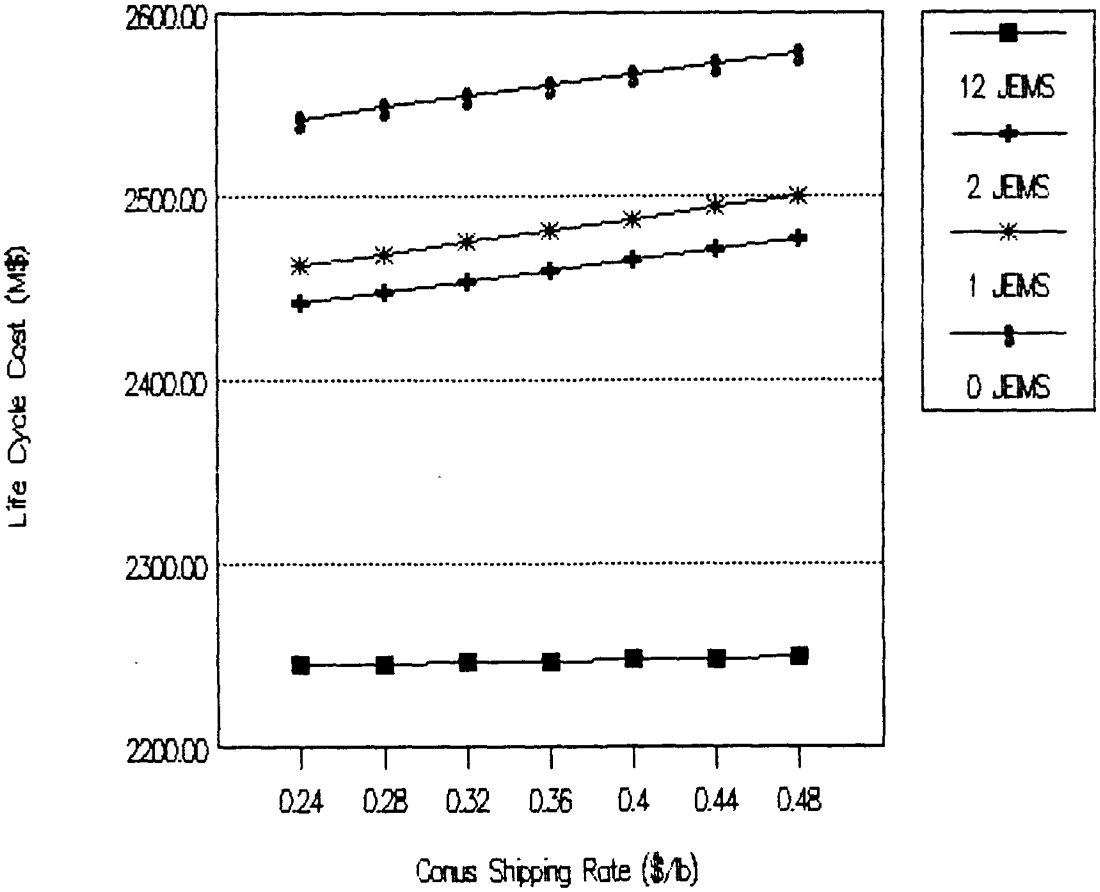

Figure 9. Shipping Rate

There are a few things to note here. First, changes in the shipping rate had little effect on three levels of maintenance. In fact, even reducing the rate 50%, from 0.48 to 0.24, only resulted in approximately $4.75 mil in savings (0.2% decrease). The curves are slightly steeper for the modified three and two level concepts. Here a

reduction from 0.48 to 0.44 resulted in LCC savings over $6 million, and the 50% decrease in shipping rate provided savings of $30-$40 mil. Although this is greater than the cost savings for the three level concept it is only 1-2% life cycle cost savings from the 50% rate decrease.

Packaging Rate. The packaging rate ($/lb.) was also varied. Again no multiplier was available, so the rate was varied from the original rate of 2.8 to 1.4 by -0.4.

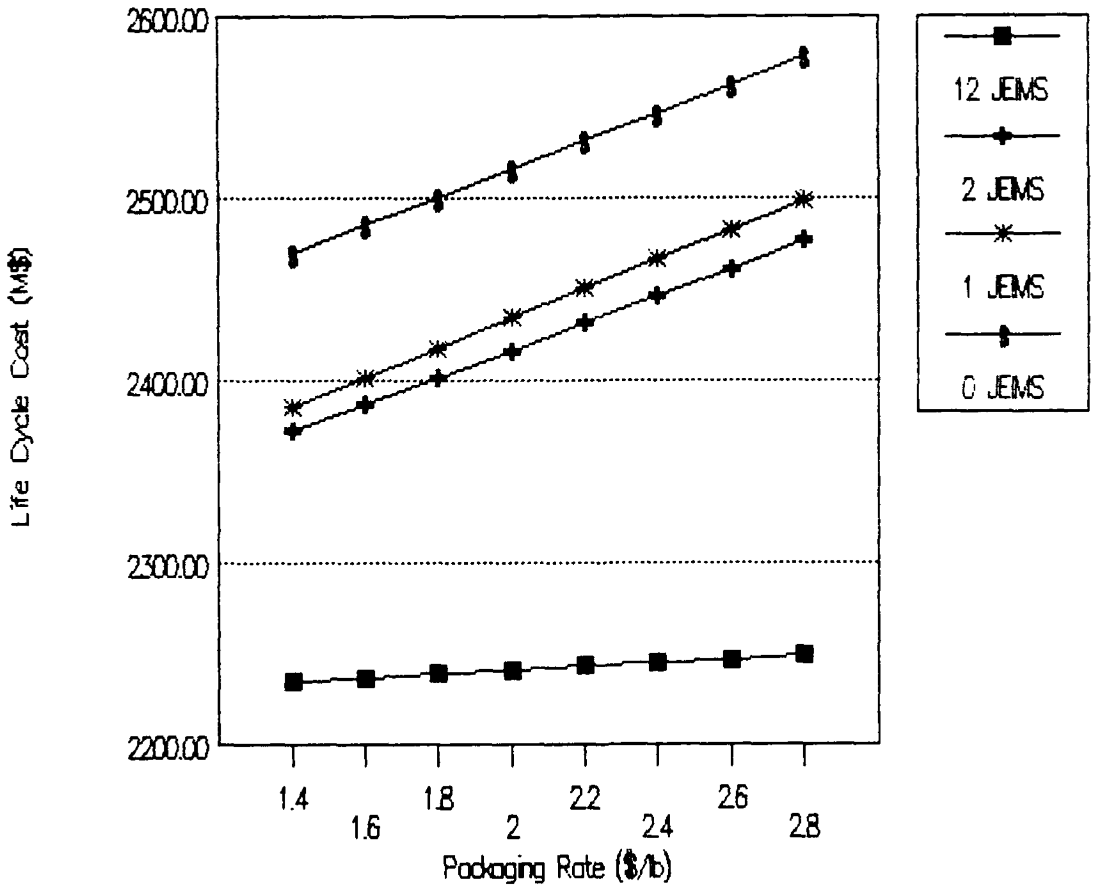

Figure 10. Packaging Rate

Like the shipping rate changes in the packaging rate did have a slightly greater effect on two and modified three level maintenance concepts than on the three level. Also, similar to the shipping rate, the curve for three levels of maintenance is nearly horizontal. A reduction in this rate from 2.8 to 2.6 (approx. 7%) resulted in cost savings of around 0.1% for the three level concept. The same change resulted in approximately 0.6% LCC savings. Again The savings is not overwhelming. A 50% change (from 2.8 to 1.4) resulted in savings of only .6% for three levels, and around 4.0-4.5% for the other concepts.

<u>Depot Repair Cycle Time (Engine)</u>. The depot repair cycle time was also varied. For this factor the time ranged from the original 58 days to 3 days by 5. The cost changes are given in Figure 11. Here one thing sticks out. The effect of the change is greatest on the two level concept. This would be expected due to the increase in the number of tasks completed at the depot. A decrease of 15 days (26%) results in less than 0.1% cost savings for three or modified three levels of maintenance. The same change results in approximately 1% savings for two levels. According to SOSCM if the time can be cut to around half (28 days), almost $60 million could be saved (over 2%). Although somewhat unrealistic when the time is reduced to 13 days and below, the LCC for

a two level concept is in the same range as the cost for a three or modified three level concept.

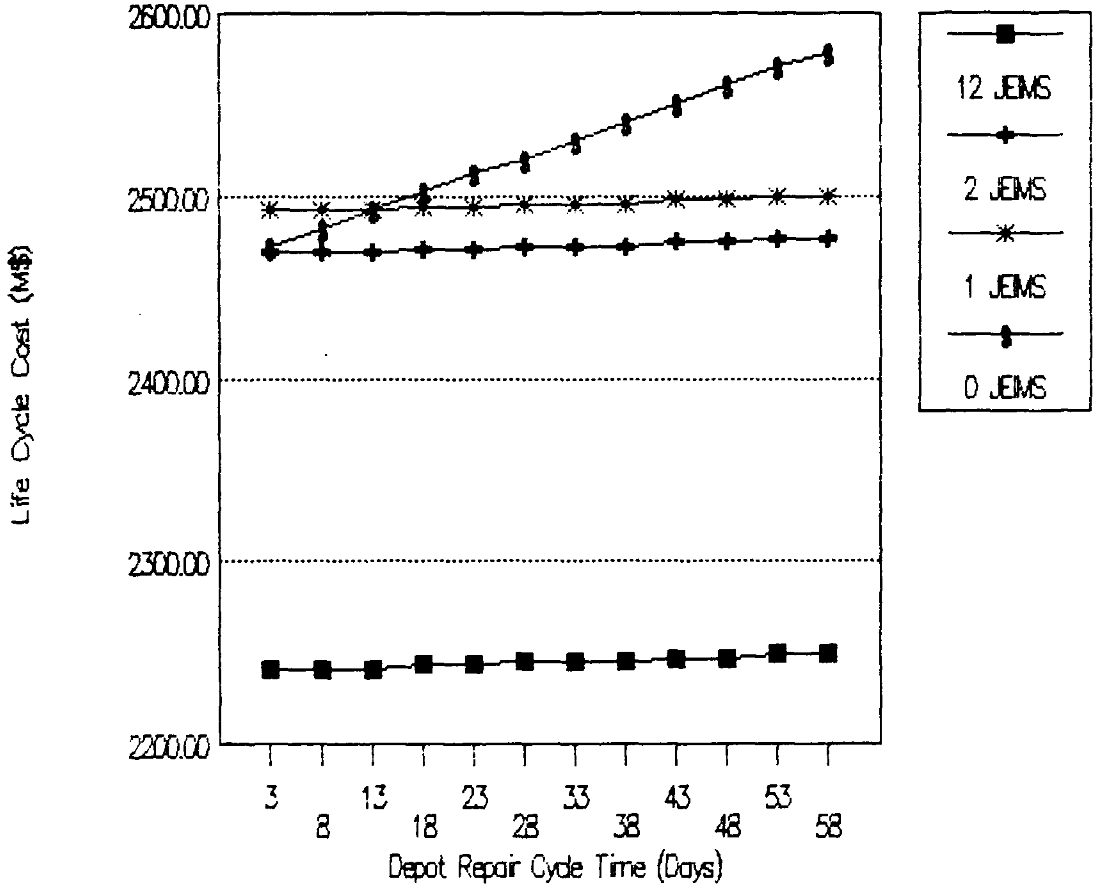

Figure 11. Depot Repair Cycle Time (Engine)

<u>Engine Weight</u>. The effect of changes in engine weight on life cycle costs can be seen in Figure 12. Here the multiplier ranged from 0.1 to 1.5 by 0.1. The difference in slopes indicates that weight changes have a greater impact on two and modified three level concepts.

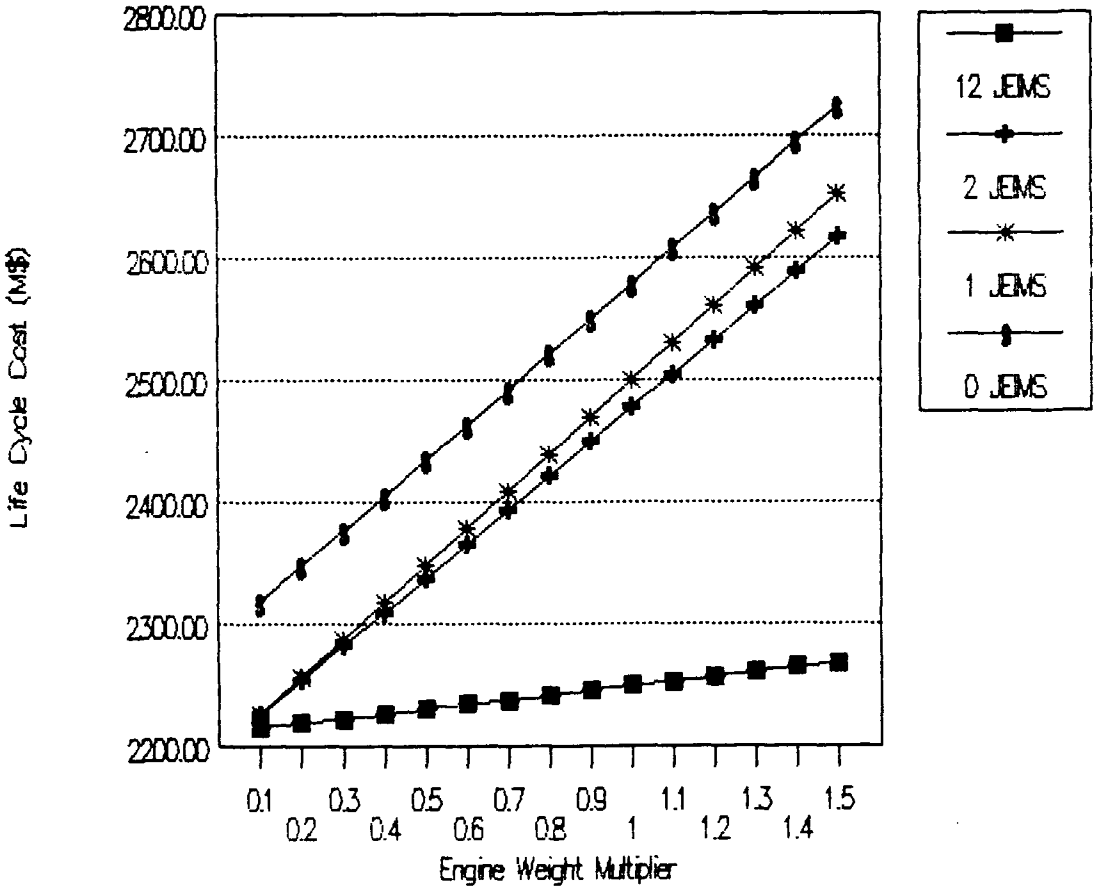

Figure 12. Engine Weight

At the lower extreme, where the multiplier is 0.1, the cost for a modified three level concept is approximately equal to three levels of maintenance. The curve for 0 JEIMS (two level maintenance) appears to be parallel to the modified three level curves (2 and 1 JEIMS). This would indicate that changes in weight have nearly the

same effect on these concepts. It is possible that engine weight is a major factor causing the increase in the second destination transportation costs for two and modified three level concepts. This would also help explain the steep curves seen for 2, 1, and 0 JEIMS. A large part of the cost increase from three to two levels of maintenance was due to transportation costs. Shipping heavier engines significantly increases these costs.

Fuel Utilization. Looking at Table 12 fuel costs were the same for all maintenance concepts. This makes sense since fuel costs depend on the cost per gallon, utilization rate (gallons/hour) and the number of operating hours. It is not surprising, then, to see that the curves in Figure 13 are parallel. These cases were run to examine the effect of fuel cost on LCC. Looking at the data, the effect is fairly dramatic. By reducing fuel utilization great savings can be realized. For example, for the 12 JEIMS case, a 25% decrease in fuel utilization from the baseline of 800 to 600 gallons/hour results in LCC savings of $287.8 mil. That is a 12.8% change. Since fuel costs are the product of operating hours, cost per gallon, and utilization, similar changes would be achieved by reducing the other factors. Utilization was used in this study because it is the only factor dependent on engine design. The others are nearly uncontrollable.

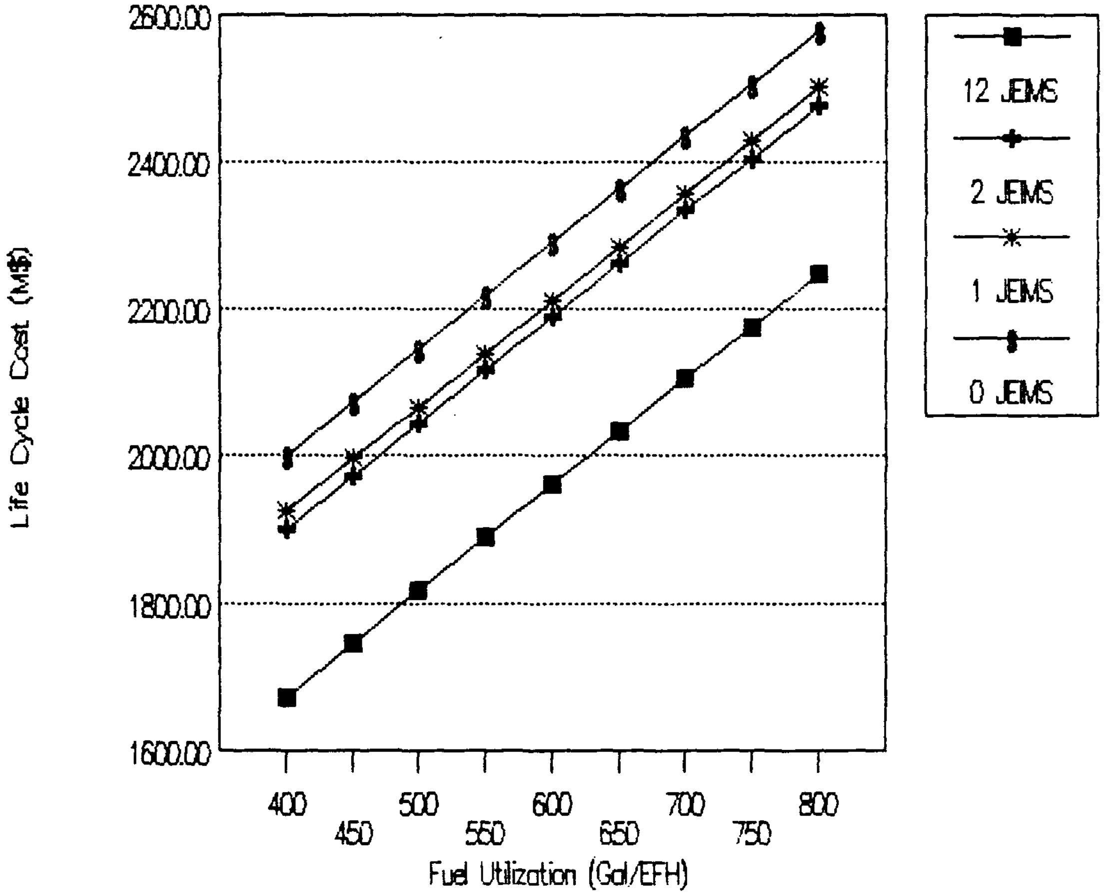

Figure 13. Fuel Utilization

Summary. Table 15 was developed to help summarize the effects of the changes in each cost factor. The table shows the impact that a 10% decrease, from the baseline, has on the life cycle cost. For example, a 10% decrease in the maintenance event rate results in a 4.2% LCC savings for three levels of maintenance (12 JEIMS).

The same 10% change produces savings of 3.8% for the modified three level cases, and 3.7% for two levels of maintenance.

Table 16. Life Cycle Cost Sensitivity

(Decrease in LCC (%) due to a 10% decrease in a cost factor.)

	Number of JEIMS			
Cost Factor	12	2	1	0
Maintenance Event Rate	4.2	3.8	3.6	3.7
Engine Removal Rate	0.1	1.1	1.2	1.5
Engine NRTS Rate	2.2	2.0	1.9	1.8
Base MMH/Event	0.1	0.1	0.1	0.1
Depot MMH/Event	1.1	1.0	1.0	1.0
Engine Cost	0.3	0.3	0.3	0.6
Engine and Other Unit Costs	1.7	1.5	1.4	1.7
Shipping	0.04	0.3	0.3	0.3
Packaging	0.1	0.8	0.9	0.8
Engine Depot Repair Cycle Time	0.1	0.1	0.1	0.4
Engine Weight	0.2	1.1	1.2	1.1
Fuel Utilization	5.1	4.6	4.6	4.5

Several things should be mentioned about the data in this table. First, a multiplier was not available for shipping, packaging, engine depot repair cycle time, and fuel utilization. Because of this, the changes in these factors were not run in even 10% increments. To make the comparison easier, the 10% increments were interpolated from the data in Appendix A. This is reasonable since the curves appear to be linear. Also, the engine cost curve, Figure 7, shows increments of 0.2.

This increment was used to decrease number of points on the plot, making it much clearer. The data in the appendix, though, is is in increments of 0.1. The 10% decrease was taken from this data.

Table 16 helps to highlight a number of things. First, the changes in some of the factors had nearly equal effects on the cost for all concepts. These factors were maintenance event rate, engine NRTS rate, base and depot MMH/event, engine and other unit costs, and fuel utilization. Changes in the other factors resulted in greater savings for the two level concept than for three levels of maintenance. A good example is the engine removal rate. For the 12 JEIMS case the 10% decrease resulted in only a 0.1% cost savings. This savings jumped to 1.5% for zero JEIMS. The table also points out that changes in some of the factors have a greater effect on cost than similar changes in other factors. A 10% decrease in the fuel utilization rate results in a 5.1% LCC decrease for three levels of maintenance. The same 10% decrease in the shipping rate only save 0.04%. Although any savings is important, facts like these can help determine the focus of future cost savings efforts.

V. Conclusions and Recommendations

Conclusions

This study produced a number of interesting results. The findings highlight some of the cost differences between two and three levels of maintenance for turbine engines. These results can be used by the Air Force to help determine the most cost effective maintenance concept for Air Force engines. The information can also be useful to engine designers. By concentrating on certain areas of engine design it may be possible to lower future operating costs.

The findings from this study can be broken into three categories. The first deals with the usefulness of the cost model, SOSCM, for this study. Next, considering the strengths and weaknesses of SOSCM, the study points out some of the cost changes which occur when moving from three to two levels of maintenance. Last, a number of cost factors were examined to determine the effect they have on overall cost and on the cost effectiveness of the various maintenance concepts.

Usefulness of the Model. Overall the cost model was very useful for this study. SOSCM has a variety of inputs and outputs which allow a user to differentiate between life cycle costs for the different maintenance concepts.

It also provides an on screen sensitivity analysis function. This function makes it easier for the user to examine the impact of changes in any number of inputs on LCC.

There are a few minor weaknesses of the model which did impact the study though. For example, SOSCM does not adjust the indirect overhead costs when a two level concept is considered. There is also no input for training and data costs, and the model does not account entirely for the savings in economies of scale which would be realized when moving from three to two level maintenance. These weaknesses have similar effects on the results. For the test case used, the cost of a two level concept was significantly greater than the LCC for three levels of maintenance. The weaknesses may have caused this cost difference to be overstated. Since traditionally three levels of maintenance has been used for engines, it is possible that either the model was not designed to estimate costs for two levels of maintenance, or that realistic data was simply unavailable to fully develop a two level model. Whatever the reason, SOSCM has some minor flaws which effect its ability to estimate the cost differences between the maintenance concepts.

Two vs. Three Levels of Maintenance. The first part of the modeling study used SOSCM to determine the changes in life cycle cost due to a change from three to two levels of maintenance. For the test case used, the two level concept resulted in a cost increase of over 14% from the three level case. Two factors account for the majority of this change. First, the number, and cost, of spare engines increased. Next, there was an increase in the second destination transportation costs. Most of the cost increase, according to SOSCM, was due to the cost of transportation. These factors made the three level concept the most cost effective for the engine model which was tested.

Cost Drivers. A sensitivity analysis was completed on a number of cost factors. There were a few reasons for this analysis. First, a comparison was made between the effects of changes in these factors on the life cycle costs for each of the maintenance concepts. A change in some cost factors had greater effects on the LCC of certain maintenance concepts than on the others. Knowing these factors would help the Air Force determine which concept is more cost effective for a particular engine model.

A few of these factors were found in this study. These were the engine removal rate, engine cost, shipping rate, packaging rate, depot repair cycle time

(for the engine), and the engine weight. In eacn case a change in the factor had a greater effect on the life cycle cost of a two level maintenance concept than on the three level case. With exception of the repair cycle time and engine cost, changes in these factors had a greater impact on the costs for the modified three level concepts than on the LCC for three levels of maintenance. For example, when the multipliers for the engine removal rate or engine weight are decreased from 1.0 to 0.1 the costs for two, three, and the modified three level cases are approximately equal. This may seem unrealistic, but the results are important. Future generation of engines may demonstrate characteristics like these. In addition, a current engine with a certain combination of these factors could result in concepts other than three levels of maintenance being the most cost effective. It may, for example, be possible that a two level concept is more cost effective for an engine with a lower weight, lower cost, and lower removal rate. There is an almost limitless number of combinations. The point is that each engine model must be treated separately. The fact that changes in certain factors effect the costs of one concept more than others means that it can not be assumed that a certain maintenance concept is the most cost effective for all types of engines. A fighter engine is

vastly different from a helicopter or cruise missile engine. Engines from one manufacturer are much different from those of another. The differences may mean maintaining them in unique ways. These things should be considered when trying to choose a maintenance concept for an engine.

Engine designers can also use the information found in this study. If an engine is to be maintained in a two level concept, a designer may wish to concentrate cost savings efforts on factors like engine weight. A reduction in weight can produce great savings in a two level concept. For a three level concept, though, engine weight has little effect, so the efforts should be focused elsewhere.

There were also some factors which had nearly the same effect on all concepts. This information is still very useful. Although the effect of changes in these factors is the same regardless of the concept, some factors result in larger life cycle cost changes. Fuel utilization is the most dramatic example. Improvements in fuel utilization can result in large long-term savings for all of the concepts. Changes in the maintenance event rate and NRTS rate also showed potential for significant cost savings. On the other hand, changes in the base maintenance man-hours per event showed only minor savings over the life of the program. Cost savings efforts should

be focused on the areas with the greatest potential savings.

To summarize the findings, for a two level concept the greatest potential cost savings appear to come from decreases in fuel utilization, engine removal rate, engine maintenance event rate, engine NRTS rate, and engine and other units costs. The same factors also have significant effects on the LCC for the modified three level concepts. For three levels of maintenance, the greatest savings can be realized from improvements in fuel utilization, maintenance event rate, engine NRTS rate, and engine and other unit costs, but changes in the engine removal rate result in considerably lower LCC decreases.

Recommendations For Future Studies

This study uncovered numerous areas for future work. These studies could provide further information on the costs of operating and maintaining Air Force turbine engines. Some of the possible studies are mentioned in this section.

One possible study deals with the costs of maintaining engines in a two level maintenance concept. It is unclear whether all the needed information is available to incorporate in models like SOSCM. The study would attempt to determine the proper inputs and assumptions concerning two levels of maintenance which would used in a cost

model. For example, according to SOSCM, the number of spare engine needed increases greatly from a modified three level to a two level concept. Data could be collected in an effort to determine whether this increase would actually be necessary. The effect of the indirect overhead, training, and data costs on the change from three to two levels of maintenance would also help improve the accuracy of the model for studies like this. Once the proper inputs and assumptions are found, current models could be updated or new ones created to help logisticians determine the most cost effective maintenance concept for an engine.

It would also be useful to use a model to examine various types of engines to find out whether certain maintenance concepts would be more cost effective for a particular type of engine. The categories may include low bypass fighter engines, high bypass transport engines, or small engines like those found in cruise missiles. The engines may also be categorized by the thrust rating or manufacturer. There are any number of classifications which could be used.

Information on other combinations of factors would also be useful. A certain maintenance concept may be more cost effective for a small efficient engine than for larger models. Experimenting with various combinations

of factors would also let the designers know how far technology must be advanced to make one concept more cost effective than others.

With the Air Force pushing to move toward two levels of maintenance, more information will be needed. This information will allow the Air Force to make decisions concerning the maintenance concepts for an engine model with greater confidence and understanding of the cost implications. This study provides only a small amount of the information required to make these decisions.

Appendix A. Life Cycle Cost Data

Life Cycle Cost (M$)

		Number of JEIMS			
		12	2	1	0
	0.5	1778.83	2006.82	2029.72	2101.91
Maintenance	0.6	1872.81	2100.81	2123.71	2197.21
Event Rate	0.7	1966.80	2194.80	2217.70	2292.51
Multiplier	0.8	2060.79	2288.78	2311.68	2387.81
	0.9	2154.78	2382.77	2405.67	2483.11
	1.0	2248.77	2476.76	2499.66	2578.41
	0.1	2196.15	2191.34	2192.76	2196.65
	0.2	2198.44	2219.50	2223.31	2237.29
	0.3	2202.73	2249.66	2255.85	2275.93
Engine	0.4	2205.02	2277.81	2286.39	2316.57
Removal	0.5	2233.31	2331.97	2342.94	2355.21
Rate	0.6	2235.60	2360.13	2373.48	2419.85
Multiplier	0.7	2239.89	2390.29	2406.03	2460.49
	0.8	2242.18	2418.44	2436.57	2499.13
	0.9	2246.47	2448.60	2469.12	2539.77
	1.0	2248.77	2476.76	2499.66	2578.41
	0.5	2002.42	2230.41	2253.31	2347.62
Engine	0.6	2050.89	2278.88	2301.78	2393.78
NRTS Rate	0.7	2101.36	2329.35	2352.25	2439.94
Multiplier	0.8	2149.83	2377.82	2400.72	2486.09
	0.9	2200.30	2428.29	2451.19	2532.25
	1.0	2248.77	2476.76	2499.66	2578.41
Base	0.5	2240.35	2468.35	2491.25	2563.44
Maintenance	0.6	2242.04	2470.03	2492.93	2566.43
Man-hours	0.7	2243.72	2471.71	2494.61	2569.42
Per Event	0.8	2245.40	2473.39	2496.30	2572.42
Multiplier	0.9	2247.08	2475.08	2497.98	2575.41
	1.0	2248.77	2476.76	2499.66	2578.41
Depot	0.5	2123.41	2351.41	2374.31	2453.06
Maintenance	0.6	2148.48	2376.48	2399.38	2478.13
Man-hours	0.7	2173.55	2401.55	2424.45	2503.20
Per Event	0.8	2198.62	2426.62	2449.52	2528.27
Multiplier	0.9	2223.70	2451.69	2474.59	2553.34
	1.0	2248.77	2476.76	2499.66	2578.41

Life Cycle Cost (M$)

		Number of JEIMS			
		12	2	1	0
	0.1	2196.57	2406.56	2427.66	2434.41
	0.2	2202.37	2414.36	2435.66	2450.41
	0.3	2208.17	2422.16	2443.66	2466.41
	0.4	2213.97	2429.96	2451.66	2482.41
	0.5	2219.77	2437.76	2459.66	2498.41
	0.6	2225.57	2445.56	2467.66	2514.41
	0.7	2231.37	2453.36	2475.66	2530.41
	0.8	2237.17	2461.16	2483.66	2546.41
Engine	0.9	2242.97	2468.96	2491.66	2562.41
Cost	1.0	2248.77	2476.76	2499.66	2578.41
Multiplier	1.1	2254.57	2484.56	2507.66	2594.41
	1.2	2260.37	2492.36	2515.66	2610.41
	1.3	2266.17	2500.16	2523.66	2626.41
	1.4	2271.97	2507.96	2531.66	2642.41
	1.5	2277.77	2515.76	2539.66	2658.41
	1.6	2283.57	2523.56	2547.66	2674.41
	1.7	2289.37	2531.36	2555.66	2690.41
	1.8	2295.17	2539.16	2563.66	2706.41
	1.9	2300.97	2546.96	2571.66	2722.41
	2.0	2306.77	2554.76	2579.66	2738.41
	0.5	2062.21	2296.86	2320.37	2359.32
	0.6	2099.52	2332.84	2356.23	2403.14
	0.7	2136.83	2368.82	2392.09	2446.96
	0.8	2174.14	2404.80	2427.94	2490.77
	0.9	2211.46	2440.78	2463.80	2534.59
Unit	1.0	2248.77	2476.76	2499.66	2578.41
Cost	1.1	2286.08	2512.74	2535.52	2622.23
Multiplier	1.2	2323.39	2548.72	2571.38	2666.04
	1.3	2360.70	2584.70	2607.24	2709.86
	1.4	2398.01	2620.68	2643.09	2753.68
	1.5	2435.32	2656.66	2678.95	2797.49
	1.6	2472.63	2692.64	2714.81	2841.31
	1.7	2509.94	2728.62	2750.67	2885.13
	1.8	2547.25	2764.60	2786.52	2928.94
	1.9	2584.56	2800.59	2822.38	2972.76
	2.0	2621.87	2836.57	2858.24	3016.58
	0.24	2244.02	2441.97	2461.87	2542.36
Conus	0.28	2244.81	2447.77	2468.17	2548.37
Shipping	0.32	2245.60	2453.57	2474.47	2554.38
Rate	0.36	2246.39	2459.37	2480.77	2560.38
($/lb.)	0.40	2247.18	2465.16	2487.07	2566.39
	0.44	2247.98	2470.96	2493.36	2572.40
	0.48	2248.77	2476.76	2499.66	2578.41

Life Cycle Cost (M$)

		Number of JEIMS			
		12	2	1	0
	1.4	2234.41	2371.48	2385.29	2469.30
	1.6	2236.45	2386.41	2401.51	2484.77
Packaging	1.8	2238.48	2401.34	2417.73	2500.25
Rate	2.0	2240.52	2416.28	2433.96	2515.73
($/lb.)	2.2	2242.56	2431.21	2450.18	2531.20
	2.4	2244.59	2446.15	2466.40	2546.68
	2.6	2246.63	2461.08	2482.63	2562.16
	2.8	2248.66	2476.01	2498.85	2577.63
	3.0	2240.77	2468.76	2491.66	2472.41
	8.0	2240.77	2468.76	2491.66	2482.41
	13.0	2240.77	2468.76	2491.66	2492.41
Engine	18.0	2242.77	2470.76	2493.76	2502.41
Depot	23.0	2242.77	2470.76	2493.76	2512.41
Repair Cycle	28.0	2244.77	2472.76	2495.66	2520.41
Time (Days)	33.0	2244.77	2472.76	2495.66	2530.41
	38.0	2244.77	2472.76	2495.66	2540.41
	43.0	2246.77	2474.76	2497.66	2550.41
	48.0	2246.77	2474.76	2497.66	2560.41
	53.0	2248.77	2476.76	2499.66	2570.41
	0.1	2214.48	2225.31	2226.50	2317.82
	0.2	2218.29	2253.25	2256.85	2346.77
	0.3	2222.10	2281.19	2287.20	2375.72
	0.4	2225.91	2309.13	2317.55	2404.68
	0.5	2229.72	2337.07	2347.90	2433.63
Engine	0.6	2233.53	2365.00	2378.25	2462.59
Weight	0.7	2237.34	2392.94	2408.61	2491.54
Multiplier	0.8	2241.15	2420.88	2438.96	2520.50
	0.9	2244.96	2448.82	2469.31	2549.45
	1.0	2248.77	2476.76	2499.66	2578.41
	1.1	2252.58	2504.70	2530.01	2607.36
	1.2	2256.39	2532.64	2560.36	2636.32
	1.3	2260.19	2560.57	2590.71	2665.27
	1.4	2264.00	2588.51	2621.07	2694.23
	1.5	2267.81	2616.45	2651.42	2723.18
	400.0	1673.17	1901.16	1924.06	2002.81
	450.0	1745.12	1973.11	1996.01	2074.76
Fuel	500.0	1817.07	2045.06	2067.96	2146.71
Utilization	550.0	1889.02	2117.01	2139.91	2218.66
Rate	600.0	1960.97	2188.96	2211.86	2290.61
(Gal/hr.)	650.0	2032.92	2260.91	2283.81	2362.56
	700.0	2104.87	2332.86	2355.76	2434.51
	750.0	2176.82	2404.81	2427.71	2506.46
	800.0	2248.77	2476.76	2499.66	2578.41

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13. ABSTRACT *(Maximum 200 words)*

This study examined the life cycle costs (LCC) for Air Force turbine engines. Specifically, the research compared the costs for two, three, and modified three level maintenance concepts. To achieve the research objectives, a LCC model, the "Super Operating and Support Cost Model (SOSCM)," was used. SOSCM is used by the Propulsion SPO, ASD/YZ, at Wright Patterson AFB to estimate costs for Air Force engines. A sensitivity analysis was run on a generic test case to determine the effect of changes in certain cost drivers on LCC. There were a few important findings. First, for this case, the LCC for the two level concept was 14.7% greater than the costs for three levels of maintenance. Two factors accounted for most of the difference. The number of spare engines required increased, and second destination transportation costs rose sharply. The study also showed that changes in some factors have a greater impact on the costs for two levels of maintenance than three. Overall, the research points out that it should not be assumed that moving to two levels of maintenance will lower costs. Engine types should be considered individually to determine the most cost effective maintenance concept.

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